Delft University of Technology
Master of Science Thesis in Embedded Systems

Adaptation of ETSI DCC for multi-lane platoons scenarios

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Abstract

Platooning involves organizing a group of vehicles with common attributes into a formation. With the help of Road Side Units, they establish Intelligent Transportation System (ITS). To facilitate communication in this system, one of the prominent communication technologies is Dedicated Short Range Communication (DSRC). In Europe, the European Telecommunication Standards Institute (ETSI) standardizes DSRC as ETSI ITS-G5 in which Decentralized Congestion Control (DCC) is used to prevent and control congestion within a wireless channel.

In this work, we determine a list of issues, namely traffic inefficiency and impaired communication, with the conventional formation of a platoon, especially an elongated one. Then, a new paradigm of multi-lane platoons is proposed with a list of modifications based on ETSI DCC to establish a prioritization scheme. These modifications are tailored to the characteristics and regulations of a multi-lane platoon. We also point out the issues of the current adaptive DCC parameters, which motivates us to develop a cross-layer mechanism called dynamic β. This proposal aims to improve the performance of the congestion control mechanism.

Our findings demonstrate the possibility of preventing channel congestion by reducing the channel load by 22% at the highest message intensity without compromising the performance of each vehicle. For dynamic β, we manifest a higher channel utilization when employing our proposal, compared to what is achieved with the default ETSI parameters. Message delivery ratio, node capacity, periodicity, and message age are also greatly improved. In short, our work provides safer for more efficient traffic.

"Try your best and see what happens" – Nguyen Duc Huy

Preface

Two years of studying at TU Delft has been a challenging yet full-of-experience and opportunity-full journey. Failures after failures, difficulties after difficulties did not put me down but built me up to become a better version. I always talked to myself "Try my best and see what happens" to myself. Self-motivation and resilience are the keys to the journey. Also, the financial situation set boundaries for my master's program.

That does not stop me to explore further in the field of Embedded Systems. Many projects and many ideas have accumulated in this project, in the field of networked systems.

The biggest drive for me during this journey is from my family. I want to give all my heart to my family and my girlfriend who are always by my side and have the highest place in my mind when I am at my lowest point. I wish they can be here with me today.

I also want to send my deepest appreciation to David Zwart and Oscar Amador Molina to pick me up when I am at my lowest points. Without them, this journey would not be complete and fulfilled. For David to help me during desperate times and for Oscar to give me inspiration and advice, my warmest thank is for them.

To Professor R.R. Venkatesha Prasad, Professor Annibale Panichella, and Suryansh, I want to send them the highest and greatest gratitude for being patient, tolerant, constructively instructive, and informative during this journey. Without them, this journey would not end on a beautiful note like this.

Nguyen Duc Huy

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23rd August 2023

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Acronyms

C-ITS Cooperative Intelligent Transportation System. 3, 26

CA Cooperative Awareness. 11

CAM Cooperative Awareness Message. iv, 3, 11, 30, 31, 35

CBR Channel Busy Rate. iv, v, 10–12, 14, 15, 28, 33, 34, 37

CH Channel. 8

DCC Decentralized Congestion Control. iii–vii, 5, 6, 9–14, 16–18, 21–23, 25, 27, 30, 31, 33–35, 40–42

DCC_ACC DCC component in Access layer. iii, 10, 11, 23

DCC_CROSS DCC component in Management layer. 10

DCC_FAC DCC component in Facility layer. 10

DCC_NET DCC component in Networking and Transport layer. iii, 10

DEN Decentralized Environmental Notification. 11

DSRC Dedicated Short Range Communication. iii, v, 4, 8–10, 26

ETSI European Telecommunication Standards Institute. iii–v, vii, 5, 6, 8–14, 16–18, 21–23, 25–27, 30, 31, 33, 40–42

FSM Finite State Machine. v, 12, 14, 16, 31, 33, 34

FSPL Free Space Path Loss. 30

ICT Information and Communication technology. 9

IEEE the Institute of Electrical and Electronics Engineers. 8, 26

ITS Intelligent Transportation System. iii, 8, 9, 13, 21

LIMERIC LInear MEssage Rate Integrated Control. 12, 15–17, 22, 23, 41

LL Lane Leader. vii, 19, 35, 37, 43

LTE Long Term Evolution (4G). 8, 26

M Member. vii, 19, 35, 37

MAC Medium Access Control. 8, 26

MANET Mobile Adhoc Network. 8

OMNet++ Objective Modular Network Testbed in C++. 26

PHY Phyiscal Layers. 8, 26

PL Platoon Leader. vii, 5, 19, 35, 37, 43

SUMO Simulation of Urban MObility. 26

TDC Transmit Datarate Control. 11, 12, 21

TPC Transmit Power Control. iii, 11, 12, 21

TRC Transmit Rate Control. iii, 11, 12, 21, 22

V2V Vehicle-2-Vehicle. v, 3, 4, 10, 21

V2X Vehicle-2-Everything. 4, 14

VANET Vehicular Adhoc Network. iv, 7, 8, 11, 16, 25, 26

VLC Visible Light Communication. 26

Chapter 1

Introduction

The advent of partially and fully autonomous cars has been transforming modern traffic. Both academic institutions and the industry invest resources in developing different technologies. These advances, either in facilitating individual vehicles or in traffic structures, aim to create a smarter and safer road. Recent years have witnessed developments in communication technologies, environment awareness abilities, or operational protocols to enhance the capability of a vehicle.

These "smart" vehicles are highly capable not only because they are technologically equipped but also because they operate with respect to others, for example, to form Cooperative Intelligent Transportation System (C-ITS). This system is partly illustrated in figure 1.1. Thanks to the establishment, a number of benefits are achieved such as safety or traffic monitoring. In detail, a collision-free environment is enhanced by the Cooperative Awareness service which ensures periodic trajectory updates among vehicles. This is executed by frequently exchanging Cooperative Awareness Message [6]. Each message may contain geographical positions, speeds, or acceleration allowing other vehicles to avoid crashing.

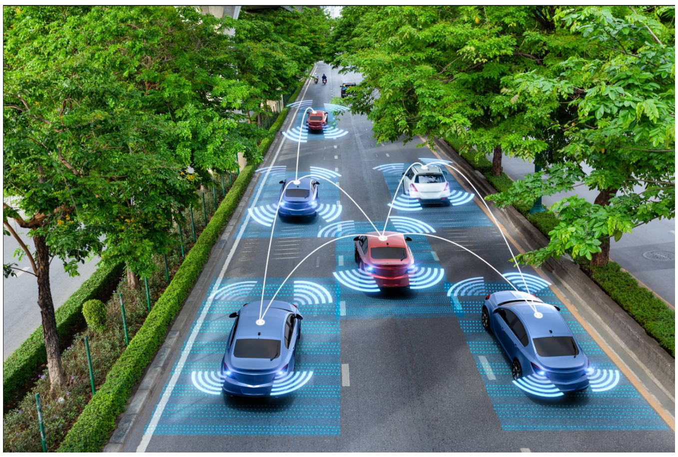

Figure 1.1: **Autonomous vehicles with V2V communication and environmental sensing [26]**

There are a number of communication technologies enabling information exchange and Dedicated Short Range Communication (DSRC) is one of the commonly used technologies. DSRC is created to support Vehicle-2-Everything (V2X) communication. One of the applications of DSRC is in platooning. Platooning is an application to form a platoon from a group of vehicles. These vehicles can share a set of characteristics such as similar equipment or the same destination. For example, figure 1.2 shows the application of V2X to manage platoons.

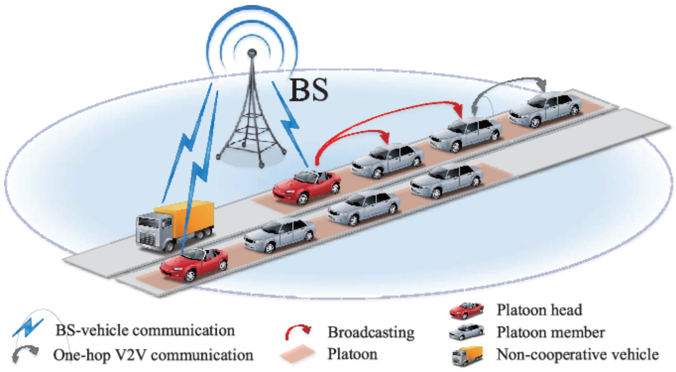

Figure 1.2: **Vehicle-2-Vehicle communication in a platoon scenario [27]**

1.1 Research motivation

From the start, a platoon was conceptualized as a train-like shape, a line with vehicles behind each other. This formation considerably reduces the air drag for the vehicles behind the front-most one, which saves fuel on the road. However, a platoon might be very long with a considerable number of platoon members stretching a great length on the road. In this situation, traffic efficiency might be impaired. A very long platoon might hinder lane changing or maneuverability of both non-member vehicles and itself demonstrated in figure 1.3 and figure 1.4. In a dynamic situation on the road, a static formation of a platoon can impair traffic efficiency.

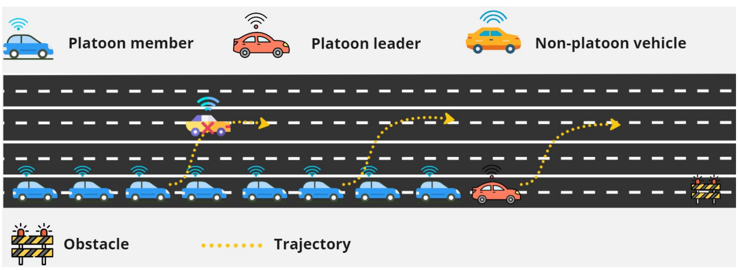

Figure 1.3: **Platoon's inability to perform lane changing**

Communication in a long platoon also raises some issues. In a normal situation, depending on the information flow, the first platoon member (mostly the

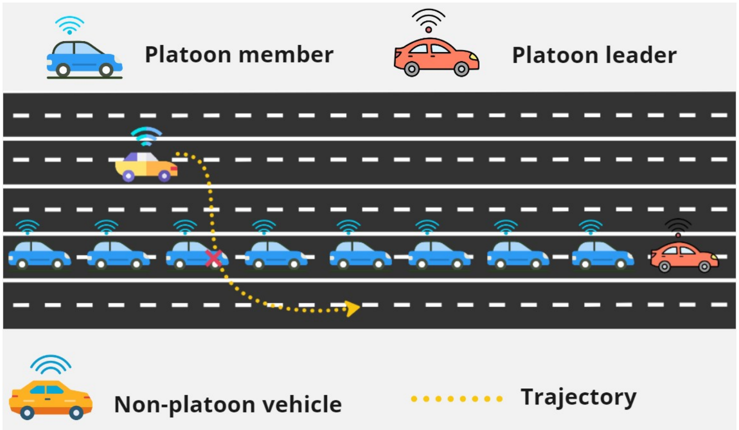

Figure 1.4: **Lane change is hindered by a long platoon line.**

Platoon Leader) needs to broadcast to its followers at the same time. However, impaired signals from the leader to the last follower or difference in reception time between the second and the last vehicles, demonstrated in figure 1.5, are challenging problems that are not completely tackled, despite a number of proposed solutions.

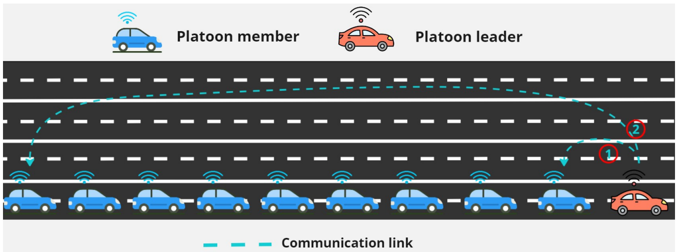

Figure 1.5: **Time difference in communication link 1 and 2**

In this work, we want to take the first step in addressing these issues by proposing a new paradigm of multi-lane platoons. This new concept aims to provide flexibility on the road, to simplify the communication issue, and to provide larger observability. We explore the characteristics of such a multi-lane platoon and regulate its communication operation while traveling on the road. We also evaluate the current ETSI DCC standard's performance on our paradigm with the consideration of the multi-lane platoon's attributes. Finally, a proposal in optimization is presented to facilitate and improve the performance of the current standard in mixed traffic (multi-lane platoons and non-platoon vehicles).

1.2 Challenges:

With this suggestion, there are a few challenges for our work:

- Currently, ETSI's documents of standards have not been focusing on the platooning application but rather tailor for single vehicles. Thus, challenges of unprecedented regulation and lack of standards emerge in our work for using the ETSI DCC.

- Secondly, other works on improving ETSI DCC did not consider our paradigm. This situation brings us little to no reference.

1.3 Contribution

Our contributions are as follows:

1. We formulate the multi-lane platoon concept including role assignment and communication, and establish qualitative requirements.
2. We evaluate the current ETSI standard and other prominent works for V2V communication with and without considering multi-lane platoon's attributes.
3. We explore and optimize the parameter in the current standard to facilitate better performance in multi-lane platoon scenarios.

Our problem statement is: *"The conventional formation of a platoon has brought a number of issues related to traffic efficiency and communication. Further, the current parameters in the ETSI DCC demonstrate drawbacks in wireless channel utilizations and reaction time toward a target load. All things considered, it is necessary to investigate a new paradigm of platoons to tackle such issues and optimize the current ETSI DCC standards for the new concept."*

1.4 Thesis outline

The thesis will be organized as follows:

1. Chapter 2: The theoretical background of this work.
2. Chapter 3: An overview of the literature and other works.
3. Chapter 4: The main content of this thesis on the concept formulation of multi-lane platoons.
4. Chapter 5: This chapter focuses on the evaluation process and the results of them.
5. Chapter 6: Results of our work are presented in this chapter
6. Chapter 7: Discussion is provided in this chapter.
7. Chapter 8: Conclusion and future work.

Chapter 2

Background

2.1 Platooning: an application for efficient transportation

A platoon is defined as a group of vehicles moving on the same route. These vehicles are at a relatively close distance from each other [11]. From the beginning, it is commonly believed that platoons are arranged in a train-like, one-line formation in which the front-most vehicle, along the traveling direction, is assigned as the platoon leader. These leading vehicles regulate different aspects of the platoon such as speed, trajectory, or the merging and the leaving operation. Inside a platoon, there might be at least one person controlling the platoon in the leading vehicle.
The information flow of a platoon can be in various establishments, demonstrated in figure 2.1.

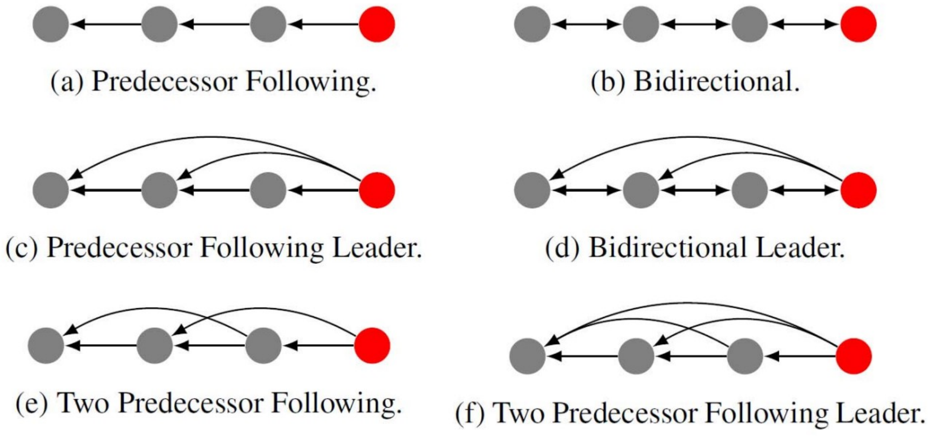

Figure 2.1: **Different information flow topologies within a platoon [1]**

Based on these typologies, the communication links between members follow the same structure. In general, the network formed by these vehicles and the communication links between them is called Vehicular Adhoc Network

(VANET), a subset of Mobile Adhoc Network (MANET). However, VANET has a set of specific characteristics [2] setting it different from its bigger concept:

1. Predictability in movement: since a platoon is a group of vehicles moving on a road, the direction of their movement is the same as the road direction and is mostly longitudinal for a certain period. Also, regulations of the road such as traffic sights, lights, or speeds are complied with by the platoon.

2. Multi-aspect conformance: in a platoon, there is the presence of humans. Thus, the operation of it needs to consider human-related aspects such as safe driving and drivers' comfort.

3. Limitless in power constraint: with a vehicle being equipped with one or many transceivers, the amount of power for transmitting messages is unlimited due to the capability of bringing more powerful batteries or using the vehicle's generator. Nevertheless, the regulation of how much transmit power to configure follows certain standards.

4. Changing network scenario: when moving a road, the presence of other vehicles, within the communication range of a platoon member, is not constant. This can be due to the difference in speed or the leaving/joining of others. Standing from the network's perspective, the node density, the communication, or the load of a channel might be varying.

Currently, to form a VANET or, specifically, a platoon communication network, there is various technology such as Dedicated Short Range Technology or cellular technology (LTE/5G).

Platooning involves different stages of the initialization, the operation, and the finishing of a platoon. Platooning can be considered a multi-discipline domain that concerns the control aspects or the communication aspects. For the former, they can be, for example, trajectory modification, speed regulation, or string stability. The latter, besides what is mentioned earlier in this section, can be routing problems, or cooperative driving [14].

2.2 Dedicated Short Range Communication - DSRC

As mentioned in 2.1, Dedicated Short Range Communication is used as a means of communication for Vehicle-2-Vehicle communication. The initial purpose of this technology started in 1991, was to provide safety for vehicles on the road through information exchange. Figure 2.2 describes the architecture of DSRC in the US.

From the PHY perspective, DSRC is allocated with 75 MHz bandwidth on 5.9 GHz. It is developed to become IEEE 801.11p standards, a part of the IEEE 802.11 family [15]. In Europe, European Telecommunication Standards Institute (ETSI) regulates DSRC as ETSI ITS-G5. Besides commonly known MAC and PHY layers, higher layers are Facility, Networking and Transport, and Security layers. With 50 MHz of bandwidth at 5.9 GHz, there are 5 channels: 1 control channel (CH 180) and 4 service channels (CH 172, 174, 176, and 178). It is regulated that if a vehicle is equipped with only one transceiver, it must be tuned to the control channel.

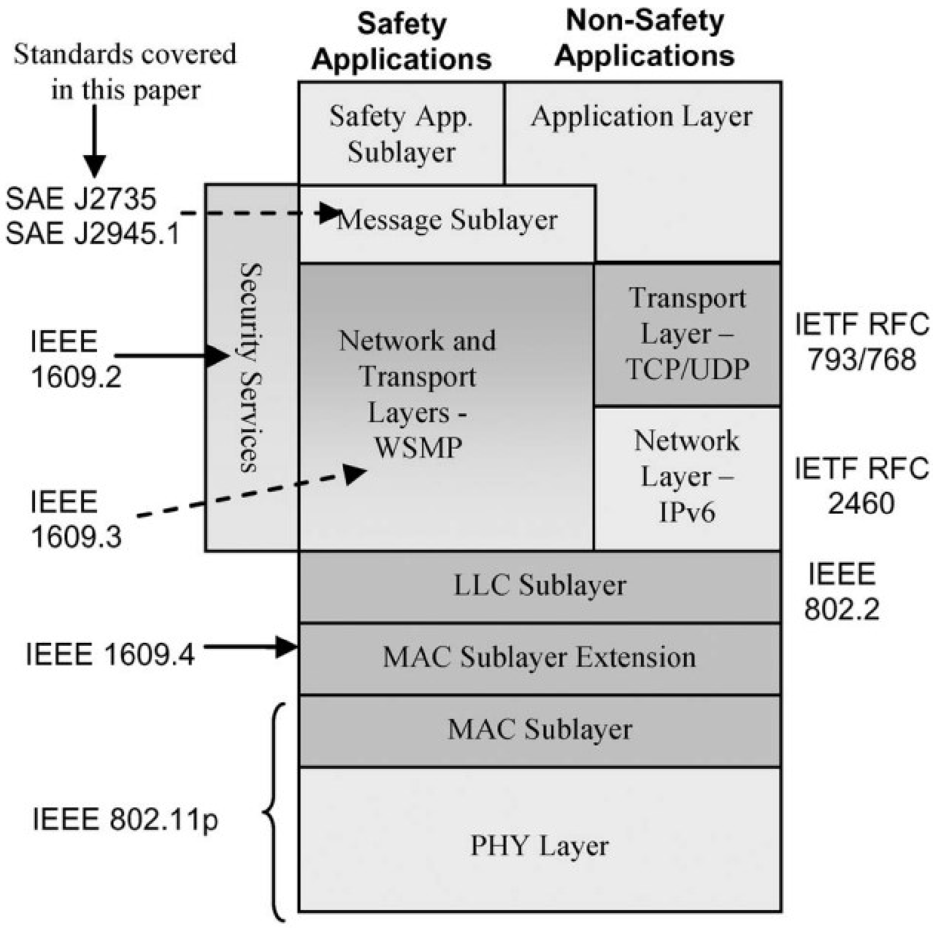

Figure 2.2: **DSRC architecture with the corresponding standard for each layer in the US [15].**

2.3 European Telecommunication Standards Institute Decentralized Congestion Control - ETSI DCC

ETSI, short for European Telecommunication Standards Institute, is a body that specializes in standardizing Information and Communication technology (ICT). It produces globally applicable standards such as radio, the Internet, or mobile. ETSI has a wide impact as it has collaboration with over 900 members from 62 countries in the world. In Europe, only standards from ETSI along with two other bodies (CEN and CENELEC) are accepted. Currently, their products are used in many regions of the world. For example, the Dutch government is using the Roadside ETSI ITS-G5 systems [5]. Another example is the partnership with 3GPP which is the main standardization body of 4G and

5G technology.

When ETSI standardized DSRC used in traffic in Europe, they propose DCC to reduce the congestion, especially in dense traffic. As regulated by ETSI, the radio channel, shared by vehicles within a geographical range, should not be congested by loads created by those vehicles [8]. Also, each transmitter is bounded to a set of requirements related to its transceiving operation [7]. DCC also helps to allocate channel resources among stations more efficiently. Thus, Decentralized Congestion Control (DCC) is issued to fulfill those demands and ensure the efficiency of V2V communication. As the name suggested, the mechanism operates on an individual level, toward a common goal. Each vehicle senses the environment to dynamically configure its transmit parameters accordingly. The status of the channel load is indicated by Channel Busy Rate (CBR). At every 100 ms (T_{CBR}), the period of time the signal strength of the channel exceeds -85 dBm (T_{busy}) is measured. The ratio between them is CBR [9].

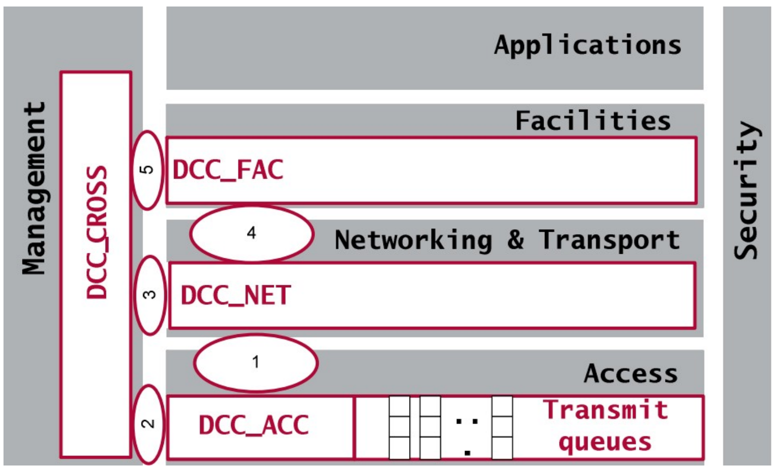

Figure 2.3: **Layers of ETSI DCC [9]**

DCC architecture (demonstrated in figure 2.3) contains the following components in different network layers:

1. DCC_ACC in Access layer.
2. DCC_NET in Networking and Transport layer.
3. DCC_FAC in Facility layer.
4. DCC_CROSS in Management layer.
5. Application layer

Among those layers, Networking & Transport layer, Access layer, and Faciliies layer are the main focus of our work.

2.3.1 Networking and Transport layer - DCC_NET

The DCC_NET [10] component is a part of the Networking and Transport layer. Two of its main responsibilities are:

- Storing and maintaining DCC-related information using the Location Table Entry Extension.
- Transmitting and receiving DCC-related information to other GeoNetworking routers using the extensions for GeoNetworking packet handling.

Working in this component is the GeoNetworking protocol which provides routing functionalities to each node. This protocol keeps track of other nodes via the Location Table. This is a data structure that stores information on nodes as entries.

2.3.2 Access layer - DCC_ACC

The component DCC_ACC [9] in Access layer is the lowest layer in the ETSI DCC architecture. It provides measured CBR to the DCC algorithm to monitor the network load. Currently, there are three parameters corresponding to three techniques for each node in VANET to manage the network load:

1. Transmit Power Control - TPC: controls the transmit power of each vehicle.
2. Transmit Rate Control - TRC: regulates the time between two consecutive packets.
3. Transmit Datarate Control - TDC: offers several data rate options for transmission.

These parameters can either be used individually or in combination.

2.3.3 Faciliies layer - safety application

In this layer, services of vehicles or platoons are deployed. The set of services can be Decentralized Environmental Notification (DEN) service or MAP data for geographical purposes. In Europe, it is regulated that if a vehicle is equipped with only one transceiver, it must be tuned to the safety/control channel. In that channel, one of the safety services that are deployed commonly is Cooperative Awareness (CA) Service [6]. This service is created to generate, receive, and process Cooperative Awareness Message (CAM) among vehicles on the road. CAM is used to create and maintain awareness of each other by providing a set of information about a vehicle. The information can be speed, acceleration, trajectory, or vehicle type. This type of message is usually generated and sent periodically within a range of $T_{GenCamMin} = 100ms$ and $T_{GenCamMax} = 1000ms$. The generation rules are summarized as follows:

1. The period since the last CAM generation is equal to or greater than the minimum time interval between two consecutive CAMs (T_GenCam_DCC) and the vehicle dynamically changes its status: more than a four-degree difference in heading angle, more than a four-meter difference from the last position, or 0.5-m/s difference from the previous speed.
2. The period since the last CAM generation is equal to or greater than the current valid upper limit of the CAM generation interval (T_GenCam) and equal to or greater than T_GenCam_DCC.

2.4 Congestion control approaches

2.4.1 Reactive DCC approach

The reactive approach in DCC is a finite state machine-based mechanism in controlling transmission parameters. This FSM originally has three states, namely Relaxed, Active, and Restrictive, each of which can only be reached from its neighboring states demonstrated in figure 2.4. Every T_{CBR}, CBR is measured to decide which state each vehicle should be in so that the transmit parameters are configured accordingly. Thus, each state is attached with a corresponding CBR level reflecting how congested a channel is.

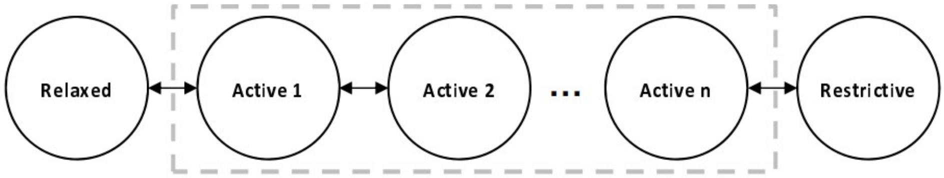

Figure 2.4: **Finite State Machine in the reactive DCC [9].**

As the name suggests, while Relaxed has the least stringent parameter limits, Restrictive restricts nodes' transmission by limiting Transmit power, Transmit rate, or Data rate. For example, Relaxed state with $CBR_{threshold}$ of 0.3 allows 10 messages per second while Restrictive state triggered by over 0.6 CBR limits the transmit rate down to 1 message per second. Besides, Transmit power is also regulated in a similar manner to restrict interference. However, this scheme is not as common as the TRC one since TPC also relates to safety insurance and distance. TDC, on the other hand, is the least touched area due to the trade-off it has [13].

The 3-state reactive DCC has some issues with its performance. That is why other papers suggest having multiple sub-states within the Active state [29]. Those are efforts in addressing issues related to this 3-state FSM such as unfairness or oscillatory behavior.

2.4.2 Adaptive DCC approach

The adaptive ETSI DCC is developed from LIMERIC [4], the work of Gaurav Bansal and his colleagues to solve the problems of the reactive DCC. Similar to LIMERIC, the adaptive DCC has three goals:

1. Convergence to a target channel load.
2. Local fairness among immediate neighboring vehicles.
3. Global fairness among all vehicles contributing to congestion.

The adaptive approach takes a different direction. It controls the transmission parameter linearly by evaluating its perceived CBR, comparing that with the target CBR, and deciding the value of δ. δ is a portion of time given to a node during which it is allowed to transmit.

To evaluate δ, the next steps are evaluated every 200 ms.

Step 1:

$$CBR_{ITS-S} = 0.5 \times CBR_{ITS-S} + 0.5 \times \frac{CBR\_L\_0\_Hop + CBR\_L\_0\_Hop\_Previous}{2}$$

CBR_L_0_Hop is the local channel busy ratio for a specific frequency channel for each ITS station and CBR_L_0_Hop_Previous is the second most received CBR_L_0_Hop.

Step 2: If CBR_{target} is larger than CBR_{ITS-S}, $\delta_{offset} = min(\beta x(CBR_{target} - CBR_{ITS-S}, G^{+}_{min})$ else $\delta_{offset} = max(\beta \times (CBR_{target} - CBR_{ITS-S}, G^{+}_{max})$

Step 3: $\delta = (1 - \alpha) \times \omega + \omega_{offset}$

Step 4: If $\delta > \delta_{max}, \delta = \delta_{max}$

Step 5: If $\delta < \delta_{min}, \delta = \delta_{min}$

More flexible than its origin with three parameters α, β, and r_c target, the adaptive ETSI DCC allows users to configure a larger number of parameters as in table 2.1.

Table 2.1: **The adaptive ETSI DCC parameters**

Parameters	Value	Description
α	0.016	Algorithm parameter
β	0.0012	Algorithm parameter
CBR_{target}	0.68	Channel load target for δ to adapt to
δ_{max}	0.03	Upper bound of the allowed time portion
δ_{min}	0.0006	Lower bound of the allowed time portion
G^{+}_{max}	0.0005	Algorithm parameter
G^{-}_{max}	-0.00025	Algorithm parameter
T_{target}	100 ms	Interval between two consecutive CBR measurement. δ is updated at twice this interval

Chapter 3

Related work

In this section, we discuss the current works in the platooning application in general including past works to tackle communication issues and part of the traffic efficiency issue. Next, research on the performance of the European standard (ETSI DCC) on platoons is presented with various approaches to both congestion control schemes of ETSI DCC. The last two parts focus on a wide range of research in improving the performance of the two schemes of ETSI DCC.

3.1 Platooning: issues and proposed approaches.

Currently, platooning is widely invested in by both academic and industrial bodies with the aim to further enhance and deploy this concept into real life. Thus, a number of research have been executed from various directions. To tackle issues with a very long platoon, L-platoon [28] is proposed. In this work, the author used a mechanism for choosing a virtual leader of a group of vehicles within a range. This allows the platoon leader to extend its control until the last vehicles. A different branch of research is to combine two prominent current communication technologies which are cellular and DSRC. When Cellular 5G is used to establish a link between base stations and platoon leaders V2X, platoon cooperation is improved in general. In addition, the author suggested a set of algorithms to control platoons, which improves traffic efficiency on the road.

3.2 ETSI DCC performance

Since the introduction of ETSI DCC, a number of research have been undertaken to evaluate the mechanism's performance in various situations, for both individual vehicles and platoons.

Different versions of the FSM-based approach were evaluated in [19]. The authors demonstrated these versions in figure 3.1, namely DCC 2+1, 2+3, and 2+5. Those abbreviations stand for 2 fixed states of Relaxed and Restrictive and a number of sub-Active states. With a platoon of 15 vehicles, they used the Inter-vehicle gap, CBR, and data age (the time elapsed since the last successfully received packet). The results of this experiment showed having

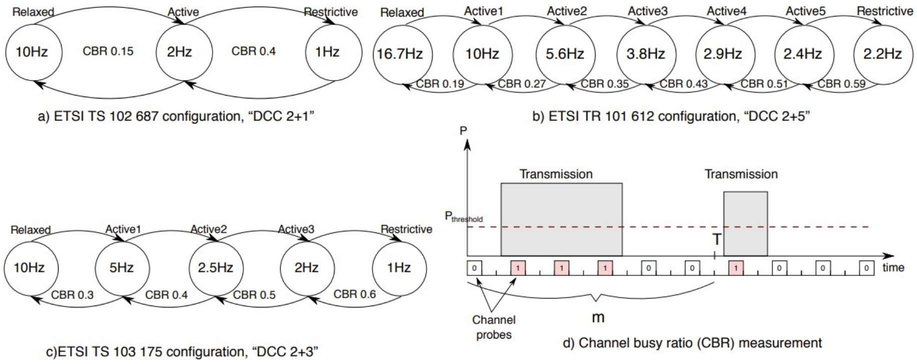

Figure 3.1: **Different version of the reactive ETSI DCC: "DCC 2+1", "DCC 2+3", and "DCC 2+5"**

higher numbers of sub-Active states yields a better performance due to a better difference between states. However, the reactive DCC has several problems including fairness and oscillation of states. The unfairness occurs in a situation in which two nodes experience the same channel load but act differently due to un-synchronization. This issue was examined in [20]. In detail, the authors showed that when two nodes switch to opposite states, one to the Relaxed state, which accidentally gives room to the restrictive switching of the other node. For state oscillation, they found out that fluctuation of perceived channel load over state thresholds does not cause rapid state changes thanks to ETSI DCC's time condition. This instability was investigated in [4]. While the latter converged to a target value of channel load, the reactive DCC oscillated wildly in a highway scenario with 1000 vehicles. They further explored the number of transmissions along the time with a sample rate of every 10s. While LIMERIC displayed a more or less uniform performance, reactive DCC had an erratic performance in this aspect. This situation, as he concluded, yields worse performance in general.

In order to improve the performance of the first release of ETSI DCC, another approach called LInear MEssage Rate Integrated Control (LIMERIC) was proposed in [4]. It was later added to the ETSI standard as the adaptive approach. In LIMERIC, each vehicle has a variable δ which represents a portion of time it has per time unit. At a given point in time, a vehicle will calculate its δ based on its previous δ and the difference between its perceived CBR and the target via

$$r_j(t) = (1-\alpha) \times r_j(t-1) + \beta \times (r_g - r_C(t-1))$$

There are three parameters in the equation:

- α: show the importance of the previous measure.
- β: a portion of the difference between the perceived channel load and the target that each node has to bear.
- r_g: the goals for δ.

When the scenario is steady, the channel load is calculated as:

$$r_C = \frac{K \times \beta \times r_g}{\alpha + K \times \beta}$$

Since LIMERIC was first introduced, other works have been developed and compared with each other. One of which performed a comparison between LIMERIC 79 ($CBR_{target} = 0.79$, adaptive ETSI DCC, and a new proposal of an ETSI DCC parameter [3]. The authors simulated three scenarios with various vehicle densities and three metrics were used: CBR and δ, packet delivery ratio, and inter-packet gap. One significant result is that the adaptive ETSI DCC works well in various traffic densities. In other words, the number of traffics does not affect the performance of the adaptive ETSI DCC. However, they also pointed out that the small chosen value of α in the standard has a very slow convergence speed.

3.3 Improvement in the reactive DCC

Since the drawbacks of the FSM-based congestion control were examined in 3.2, there have been a number of attempts to improve the performance of the reactive approach. Besides exploiting the number of sub-Active states, tuning one or multiple transmit parameters and checking the status of surrounding vehicles are also considered.

Seeing the unfairness problem in the reactive approach, the articles in [16] suggested a check on the surrounding node before any state change. The authors pointed out the difference in states among close vehicles which uses a three-state FSM. After including state numbers in a safety message and averaging out all the state numbers from received messages, state changing was executed. The Jain fairness index showed that the proposed method improved the fairness among nodes considerably, especially around 80 to 100 vehicles/lane/km.

In the ETSI standard of DCC, two of the three transmit parameters that each vehicle can configure are transmit power and transmit rate. Those are the motivation for the work in [17]. The authors explored the performance of using each parameter and then they proposed a joint scheme that combines both power and rate. In the joint control, each level of transmit power, covering a specific area, corresponds to a particular traffic density. Each pair of transmit power-density has an aggregate load, smaller than the target load. As a result, the joint control scheme reduces the congestion in VANET. However, the author clarified that each scheme was meant for different purposes: rate control for nodes with equal transmit power and no possibility of application requirement; transmit power scheme for nodes with constant and range-based varying transmit rates. Power+rate gave flexibility in trading off two parameters.

3.4 Improvement in the adaptive DCC

Based on the unexplored effects of LIMERIC's parameters, other works have explored the possibility of this linear distributed method.

After publishing LIMERIC with $\alpha = 0.1$, $\beta = 0.0067$, and $CBR_{target} = 0.6$, the authors in [23] tried a different set of parameters, $\alpha = 0.1$, $\beta = 0.0033$, and $CBR_{target} = 0.79$. By setting a higher value of target load, the perceived CBR is higher, which compensated to a high value of α. This was clarified in the paper [25]. In this work, a comparison between two values of α was shown: 0.1 and 0.016. I was shown that a small α yields a closer value to the target load but has a slow convergence speed. On the other hand, a high α has the opposite characteristics. This is the basis for a new proposal: dual-α. By employing this mechanism, a faster response time was achieved compared to that of the standard ETSI DCC. The performance of dual-α was further evaluated in [3]. The result is that while in a steady state, dual-α has an equal performance as the standard adaptive ETSI DCC, this new mechanism outperforms in a transitory situation.

Another notable research was executed in [18]. Based on the basis of LIMERIC, the author observed the scalability problem in which during high-density situations such as rush hours, the performance was damaged by a fixed β. That was why SWeRC - Self-Weighted Rate Control, independent of traffic densities, was proposed. In his proposal, a weight was calculated based on the previous rate and the maximum local node capacity. This weight affected β and the difference between the previous rate and the target rate:

$$r_j(t) = (1 - \alpha) \times r_j(t-1) + \omega \times \beta \times (r_g - r_C(t-1))$$

The effect of a range of α was examined. By doing this, the author achieved a more robust reaction and less oscillation regardless of the number of vehicles. As a result, this optimization provided a higher frequency by its closer value of rate to the target, and unaffected performance and stability even with 1000 vehicles.

Chapter 4

Methodology

The focus of this chapter is on the formulation of multi-lane platoons, their characteristics, and their operations and regulations in terms of communication. Then, a proposal on a dynamic β to optimize the adaptive ETSI DCC is presented

4.1 Multi-lane platoon paradigm

We define the multi-lane formation of a platoon in our scenario as follows: a temporary state of a platoon in which its formation is spread in multiple parallel lanes on the road. The formation can be changed based on the surrounding traffic condition. The communication aspect utilizes the characteristics and operation of the multi-lane platoon to optimize its transmit parameters at the vehicle level. The possible formations of the platoon are demonstrated in figure 4.1.

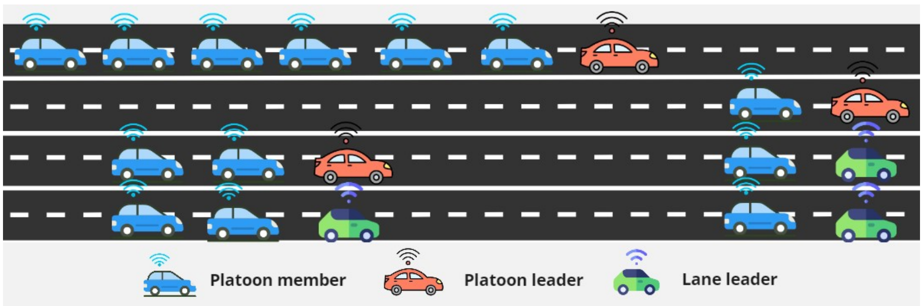

Figure 4.1: **Possible formations of a platoon: 3 lanes, 2 lanes, or conventional formation.**

On a road, different lanes experience various conditions such as lanes with obstacles, lanes for prioritized vehicles, or ones with traffic jams [12]. In such a situation, moving from the lanes with obstacles to another faster lane can benefit platoons. This feature, in general, provides the efficiency of moving for not only the platoon itself but also other vehicles.

4.1.1 Role assignment in multi-lane platoons

In a multi-lane formation, based on the relative positions each platoon member might experience, we propose the regulation of the role assignment as follows:

- Lane leader (LL): based on the direction of traffic, the lane leader is the front-most vehicle of each lane. It can be considered the leader of its subgroup - the group of vehicles in that lane.

- Platoon leader (PL): the main leader of the whole platoon as in the original concept. The platoon leader is also the lane leader of its lane.

- Platoon member (M): other members of the platoon except for the lane leader(s) and the platoon leader.

An example of roles in a two-lane formation is demonstrated in figure 4.2.

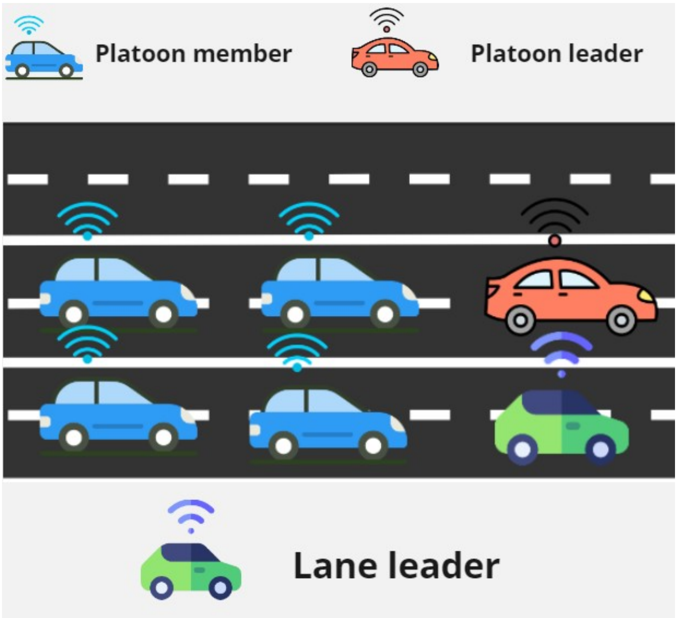

Figure 4.2: **Example of role assignments in a multi-lane platoon.**

Lane leader(s) and platoon leader(s), with such role assignment and position within a platoon, have the highest likelihood of colliding with other vehicles.

4.1.2 Communication operation

To ensure traffic safety in a scenario, we propose the following communication links regarding each entity's attributes:

- Only the lane leader(s) and the platoon leader can communicate with non-platoon vehicles or lane leaders and platoon leaders from other platoons.

- Each member (not lane leader and platoon leader) only needs to communicate with its lane leader.

- Lane leader needs to communicate with the platoon leader.
- Lane leader and platoon leader also need to communicate with their sub-platoon members.

With the proposal of role assignments in 4.1.1 and the communication link between members and non-platoon members, communication originating from the lane leaders and the platoon leaders is crucial to ensure the safety of the whole scenario.

In a scenario where one or many platoons are present, there are two levels of importance assigned to inter- and intra-communication links:

1. High priority links: links that come from lane leaders, platoon leaders, or non-platoon vehicles. This is because those entities on the road are exposed to a bigger risk of collision, based on the traffic direction.
2. Low priority links: links that come from platoon members to their lane leaders. These vehicles mostly follow the direction of the frontmost vehicles which are lane leaders.

An example of communication links of a two-lane platoon with its level of importance is demonstrated in figure 4.3.

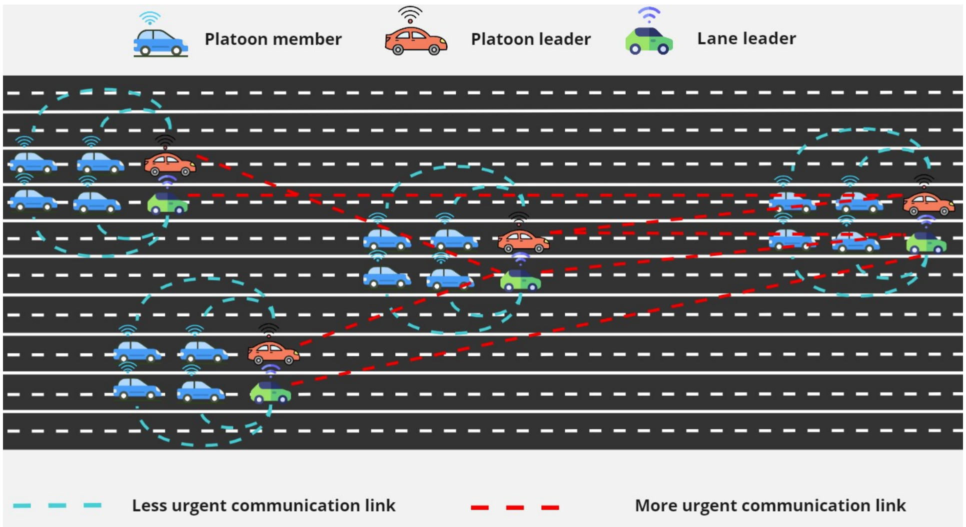

Figure 4.3: **Example of communication links in a multi-lane platoon.**

4.1.3 Multi-lane platoon's constraints

With the situation, the role assignment, and the communication operation described, we have a set of requirements for a platoon in a multi-lane formation. Since the concept of multi-lane platoons has not been explored and standardized before, these requirements are qualitatively defined.

1. **Data age**: this constraint ensures each message, especially the safety one, contains updated information about its sender.

Although this aspect is ensured in V2V communication between individual vehicles, it needs to be emphasized in multi-lane platoon scenarios, especially in the communication between a lane leader and a platoon leader in a group. It should not be too old so that the cooperative awareness information in each message is not outdated.

2. **Periodicity**: this aspect aims to maintain a frequent and uninterrupted link between nodes in a multi-lane platoon scenario.
   Similar to the Data age, the emphasis is still on the link between a lane leader and a platoon leader within a group. Data age and Periodicity are used to ensure the latest and constant information of a node, of its followers, and its awareness is updated to the other high-priority members within a platoon.

3. **Adaptable transmit power**: based on the relative distances to a receiver perceived by the sender, transmit power is adaptably configured to this length. The graphical position of nodes can be exchanged via messages.

4. **Moderate data rate**: although ETSI DCC facilitates different levels of data rate from 3 Mbps to 12 Mbps, 6 Mbps is widely used and consented as a standard data rate. In addition, this level is proved to be the optimal data in most scenarios [13].

4.2 Proposal on the ETSI DCC for Multi-lane platoons

Based on the ETSI DCC standard, there are three parameters for controlling the transmission of each ITS: Transmit Power Control (TPC), Transmit Datarate Control (TDC), and Transmit Rate Control (TRC). About the Data rate, it is commonly accepted that 6 Mbps is the optimum data rate, which is experimented with in various scenarios [13]. In this thesis, transmit power and transmit rate are the main focuses of our proposal.

4.2.1 Transmit power - TPC

While traveling on a road, a platoon can exhibit various formations which can last for a certain amount of time. During a temporary formation, each member is, assumingly, able to obtain the relative distances between itself and other members, especially its intended receiver(s).

With additional information on the propagation model, receiver sensitivity, and the relative distance between the intended transmitter and receiver, a member can calculate the amount of transmit power needed for transmission. Thus, during a formation, different members will have a different level of transmit power. These various levels also represent the level of importance of communication within a multi-lane platoon:

- Full transmit power: Platoon leaders, lane leaders, and non-platoon vehicles.
- Distance-based transmit power: other members within a multi-lane platoon.

The result of adaptable transmit power is demonstrated in figure 4.4.

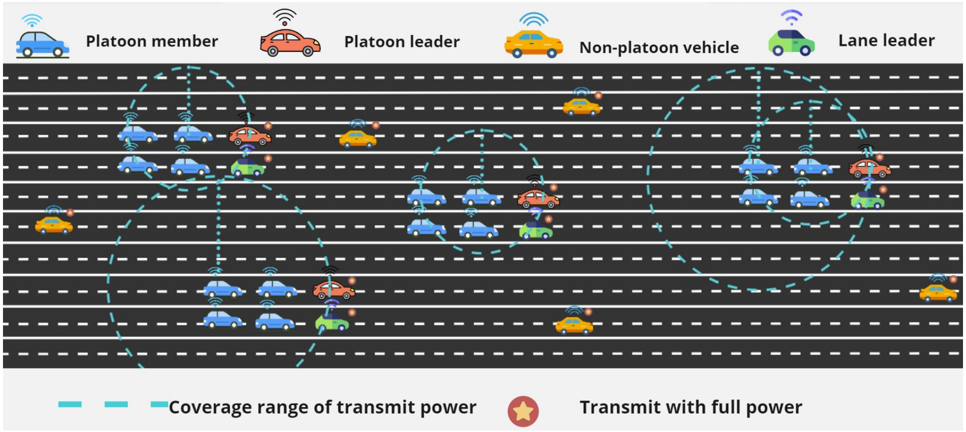

Figure 4.4: **Example of transmit power of each member within a multi-lane platoon.**

4.2.2 Transmit rate - TRC

The second way to represent the priority in multi-lane platoon communication is via the safety message generation rate. While traveling on a road, the front-most vehicles of a platoon are exposed to a higher risk of collision. Thus, besides their responsibility of broadcasting safety messages to vehicles outside their platoon, lane leader(s) and platoon leader must both communicate with each other and command their followers. To ensure safety on the road for every vehicle, it is needed for lane leader(s), platoon leader(s), and non-platoon vehicles to broadcast messages at a higher rate than that of platoon members.

For initial testing, based on the number of entities that a platoon leader, a lane leader (their members and vehicles outside the platoons), and platoon members (their lane leader only) talk with, we set the message generation frequency of the platoon leader/lane leader(s) to be twice as high as that of platoon members.

4.3 Dynamic β: optimizing for a homogeneous and a mixed scenarios

In theory,LIMERIC [4] or the current adaptive ETSI DCC has three goals:

1. To converge to a desired channel utilization level (channel load).
2. To achieve local fairness among immediate neighboring vehicles.
3. To achieve global fairness among all vehicles contributing to congestion.

Among the three goals, the first one is possible thanks to LIMERIC's parameters α and β which were clearly explained. In short, α is a parameter demonstrating the ability to react to changes. While a small value of α allows a CBR value close to the CBR_{target}, the speed of convergence is slow. On the other hand, a big value of α improves the convergence speed but larger deviance to CBR_{target}.

In our work, there are two cases: homogeneous multi-lane platoons and mixed scenarios (containing multi-lane platoons and non-platoon vehicles):

1. Homogeneous traffic: The value of β in this case can be easily evaluated by increasing β of ETSI DCC by 2 or 3 folds, which leads to a higher value of β (0.0036, for example). This means the number of transceivers perceived by each vehicle reduces since fewer nodes participate in the global environment.

2. Mixed traffic: A more realistic situation is when there is a mix between single vehicles and multi-lane platoons. In this case, the number of active users is unknown since there might be one single vehicle, and the rest are organized into multi-lane platoons and vice versa.

Since the two cases deal with the number of active nodes which is the nature of β, we only focus on optimizing this adaptive DCC parameter.

4.3.1 Adaptive ETSI DCC: efficiency issue

β represents the share of each vehicle based on the difference between the current channel load and the target channel load. In theory, the value of β should be the inverse of the number of active nodes sharing the same medium. That is why β is a bit trickier to evaluate. Knowing or estimating the number of nodes is not possible in the access layer. In the adaptive ETSI DCC, β is 0.0012, equivalent to 833.33 vehicles and convergence guarantee up to 1653.33 vehicles. However, when putting this value into a multi-lane scenario, the fixed value of β creates slow convergence and update rate. In a dynamic situation that requires a fast response, it might not be able to provide safety. Thus, the β value of 0.0012 makes the channel underutilized for a longer time, or the channel resources are wasted.

4.3.2 Approach: cross-layer cooperation.

With the information from the Location table in the Networking & Transport layer, the DCC access is likely to calculate the β for the adaptive ETSI DCC. This is possible because the number of entries in the Location Table is approximately equal to the number of active nodes. This information is periodically transmitted to the DCC access layer which calculates β. By performing that, DCC_ACC is able to set β dynamically.

There might be two cases when using dynamic β. First, the Location Table is used to store information of other nodes not only within one hop but also multi-hop. However, since our experiment only considers one hop communication link, the estimation of K can be more precise. In the worse scenario, it is more likely that although entries in the Location Table might include nodes within multi-hop, the estimation might be still better than the fixed β in the adaptive ETSI DCC. Secondly, in case the estimated K from the Location Table might not be lower than the actual number, there is still room for such a difference. This is because the adaptive ETSI DCC is developed from LIMERIC in which the convergence is guaranteed to a number from the following inequality:

$$\alpha + \beta K < 2[4]$$

Thus, in either case, what we achieve is still better than using the fixed β from the adaptive ETSI DCC.

Chapter 5

Evaluation approach and Testbed Setup

In this chapter, we present our experiments from setting up the experiments to configuring each scenario. Also, we explain a set of metrics for evaluating simulation results.

5.1 Evaluation components

In our work, the evaluation contains two parts:

1. Part 1: Evaluation of our proposal on ETSI DCC in a multi-lane platoon scenario.

2. Part 2: Experiment on the dynamic β.

The focus of the first part is to compare the results from two configurations: with and without our proposal from section 4.2. Experiments of both configurations share the same scenario and differ by the transmit power and message generation rate.

In part 2, we aim to test the performance when employing the dynamic β mechanism and compare it with that when using the default setting of the adaptive ETSI DCC. In this experiment, there are two sub-parts: multi-lane platoons only (uniform traffic) and multi-lane platoons with individual vehicles (mixed traffic).

5.2 Simulation Framework

This section introduces the traffic simulator that we use in our work and the related framework that it is developed from.

5.2.1 Veins - a VANET simulator

Veins [24], developed by Christoph Sommer from Telecommunication Network Group from TU Berlin, is an open-source framework for simulating Vehicle-2-

Vehicle network operation. This is a combination between OMNet++, a network simulator, and SUMO, a traffic simulator. Its architecture is demonstrated in figure 5.1. As an open-source framework, Veins allows users to create a highly detailed scenario with desired behaviors of each node. To be specific, SUMO helps them to create roads (such as direction, speed limits, or sizes) or to control traffic (such as vehicular density, generation of vehicles, or their speed). Then, these structures are linked to OMNet++ in which the network perspective of a simulation is defined. For example, Medium Access and Physical Layer are configured in OMNet++, or wireless communication of each node is established. A very important feature of Veins is the ability to integrate third-party models into it such as LTE (4G), or Visible Light Communication (VLC). However, Veins is designed based on DSRC standards from the US. That is when Artery comes to play.

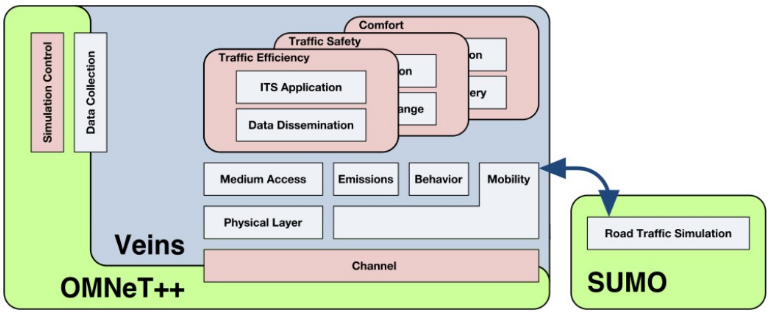

Figure 5.1: **Architecture of Veins [24]**

5.2.2 Artery - Extension of Veins for ETSI ITS-G5

Artery [21] is an extension of Veins. This is the work of Raphael Riebl to accommodate VANET simulation of Veins with the European standard.

Besides the IEEE 802.11 model like Veins, Artery allows users to use the INET model for PHY and MAC. The difference from Veins comes from the deployment of Vanetza which is an open-source implementation of the ETSI C-ITS protocol suite. Artery allows users to implement a number of interesting features such as a storyboard for environmental dynamic changes or sensors for each vehicle.

Other features and components of the Artery can be observed in its architecture in figure 5.2. To begin, Artery provides a number of examples that instruct users to create their VANET simulation. Also, the authors wrote a chapter in the book "Recent Advances in Network Simulation" [22] to guide beginners to use this framework, in a more detailed manner.

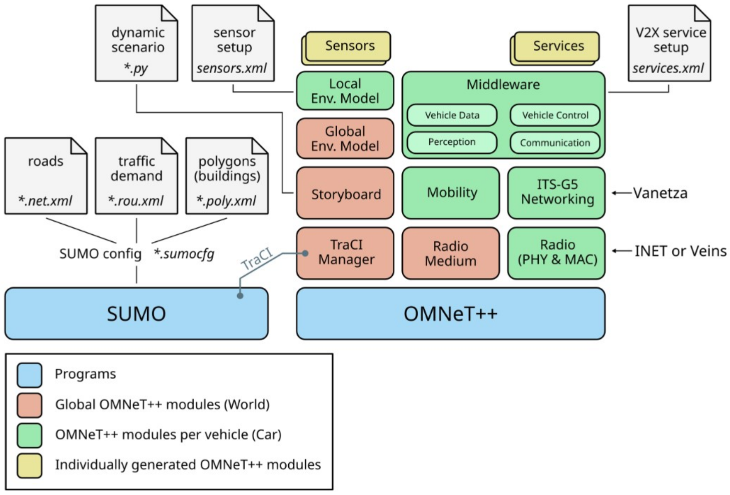

Figure 5.2: **Architecture of Artery [21]**

5.3 Scenarios

5.3.1 Evaluation of our proposal on ETSI DCC's in a multi-lane platoon scenario

The road in this experiment is a highway that is one kilometer long and has six lanes in one direction. All the vehicles are organized into multi-lane platoons each of which spans two lanes. Thus, there are three streams of multi-lane platoons in the scenario. In a platoon, there are six vehicles arranged in a two-by-three formation. The distance between each member is five meters. It is important to note there have not been any documents about the density of platoons, including multi-lane ones. Thus we rely on ETSI TR 101 612 to obtain a "sparse" density. On a "major" lane (comprising two regular lanes), each platoon is 50 meters away from its closest one. All platoons move in the same direction at the same speed. The formation of platoons and the road are demonstrated in figure 5.3. In short, there are 138 vehicles organized into 23 multi-lane platoons.

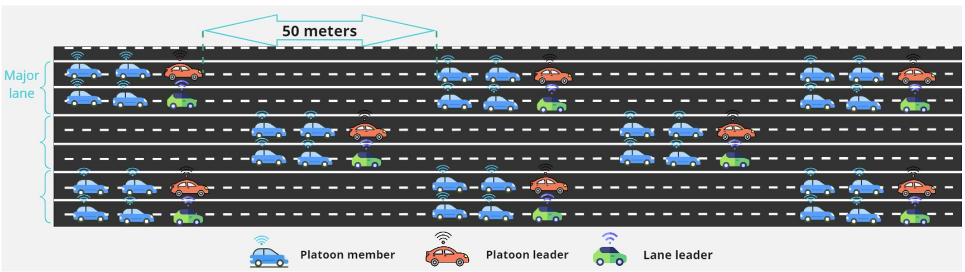

Figure 5.3: **Scenario for the first experiment: highway - 6 lanes - 1 direction**

5.3.2 Experiment on Dynamic β

The first sub-part focuses on a uniform scenario in which there are only multi-lane platoons on the road.

The second sub-part describes a mixed traffic scenario in which individual vehicles travel with multi-lane groups. In this experiment, four additional lanes, with similar characteristics, are added to the current road. In terms of vehicles, besides the group of platoons as group 1 in the earlier experiments, there is a group of individual vehicles as group 2 which are densely close to each other. This organization is to create the highest interference to group 1. The operation of group two is described in figure 5.7. In short, the scenarios of both parts are described in the table 5.1.

Parameter	First part	Second part
Road	6 lanes - 1 direction	10 lanes - 1 direction
Vehicles	138 vehicles into 23 platoons	Uniform traffic: 138 vehicles as platoons into 23 platoons Mixed traffic: 138 vehicles as platoons (group 1) and 80 individual vehicles (group 2)

Table 5.1: **Summary of traffic configurations of the second experiment.**

5.4 Evaluation Metrics

5.4.1 CBR

First of all, we want to see how the CBR is affected when applying our proposed modification in the first experiment. Next for the dynamic β, we also need to see the behavior of CBR throughout the simulation. Mostly, the channel's reaction in the presence of interference is our interest. To be specific, we want to see how close the average CBR resulting from dynamic β is to the CBR_{target} compared to that of default β. Also, we want to observe how stable the channel load is and how fast the CBR converges.

5.4.2 Delivery rate

This metric is to measure the success rate of delivering messages throughout the simulation time. It is calculated as the number of received messages at the receiver over the number of sent messages from the transmitter. The rate can be affected by the distance between the transmitter and the receiver or by the number of collisions caused by inefficient channel control.

Based on the set of requirements mentioned in section 4.1.3, this metric is very crucial since the safety of a multi-lane platoon might not be ensured if a large portion of the information is lost during the transmission. That also means the channel's resources are wasted.

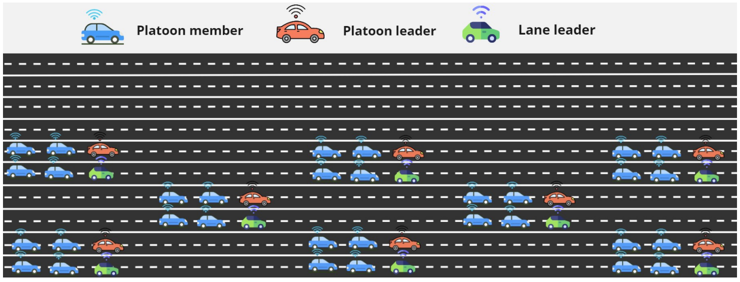

Figure 5.4: **Phase 1: Multi-lane platoons travel on the road without individual vehicles**

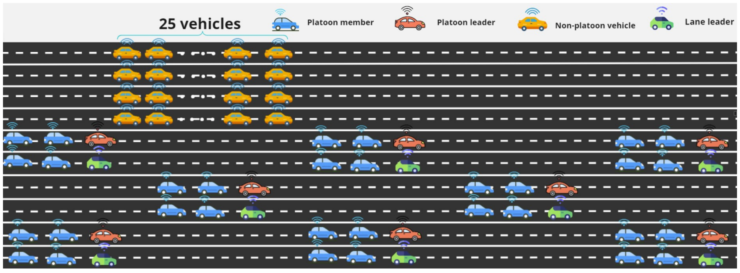

Figure 5.5: **Phase 2: a group of individual vehicles enters the scenario**

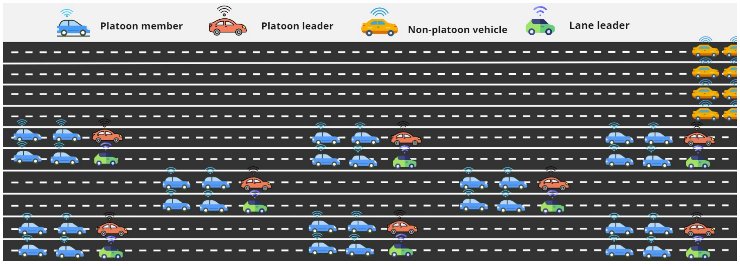

Figure 5.6: **Phase 3: After traveling with multi-lane platoons, the group of individual vehicles moves away.**

Figure 5.7: **Phases of the scenario in the second experiment**

5.4.3 Inter-message time

Inter-message time is the time between two consecutive messages perceived by the receiver. In our case, it is equal to T_GenCam_DCC. However, to avoid collisions, a message might not be sent immediately, making this metric different than usual.

In our scenario, since each vehicle is aware of each others' status via CAM messages, there must be periodic updates between vehicles in a scenario.

5.4.4 CAM age

This metric measures the time from a CAM message is made at the transmitter until the time it is received. It is measured at the receiver's end by making use of a field called generation delta time which is compared with the time the message is received. CAM age can be understood as jitter from the receivers' perspective.

CAM age is crucial in high-priority transmission since it makes sure the awareness information of a vehicle is not outdated.

5.5 Experiment Configurations

5.5.1 Environment Configuration

Since the road model in our experiments is a highway, it is acceptable that the propagation model is free space path loss. The formula is as follows:

$$FSPL = 20log_{10}(d) + 20log_{10}(\frac{4\pi}{c}) - G_t - G_r$$

- d: the distance between the transmitter and the receiver.
- c: the speed of light $300,000,000$ m/s
- $G_t \& G_r$: the antenna gain at the transmitter and the receiver, respectively.

5.5.2 ETSI DCC's transmit configuration for multi-lane platoons

Regarding transmit power, a vehicle needs to recognize the propagation model of the environment it is in. This information with the receiver sensitivity allows each node to estimate how much transmit power it needs to use. In our experiment, the receiver sensitivity is set to -85 dBm, as regulated in the ETSI DCC standard. The transmit power is calculated as follows:

$$P_{transmit} = FSPL + P_{receive}$$

With the distance and the antenna gain (normally both of them are 1 dB), a vehicle can calculate the needed transmit power. In our experiment, within a multi-lane platoon (six vehicles in two lanes), the relative distances between pairs of transmitter-receiver are demonstrated in figure 5.8. Thus the corresponding transmit power of each member (apart from platoon leaders, lane leaders, and non-platoon vehicles) can be found in figure 5.8. It is needed to mention that although the theoretical values of transmit power are calculated, they are not precisely correct due to the simulation. Thus, we calibrate and achieve those values from figure 5.8 via various trial experiments.

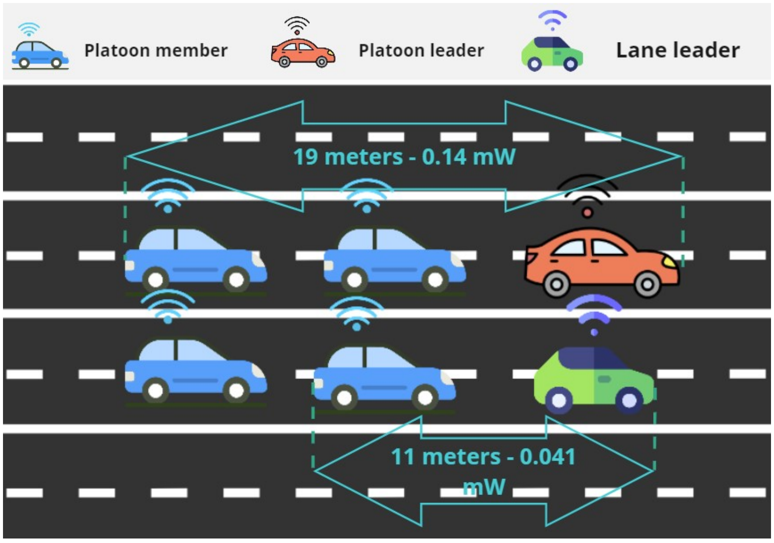

Figure 5.8: **The relative distance between platoon members and their corresponding receivers and its experimental transmit power.**

In terms of CAM generation frequency, as mentioned in section 4.2.2, the message frequency of lane leaders, platoon leaders, and non-platoon vehicles is twice that of platoon members. The specific configuration can be found in table 5.2. These frequencies are commonly chosen to put more load on the channel.

Table 5.2: **Message generation frequency**

Message Frequency	PL/LL	M
Dynamic	2 Hz*	Dynamic
2.5 Hz	2.5 Hz	1.25 Hz
5 Hz	5 Hz	2.5 Hz
10 Hz	10 Hz	5 Hz
20 Hz	20 Hz	10 Hz

* This is the maximum value of the dynamic generation frequency

In the second experiment from section 5.3.2, we only run the simulation in the dynamic CAM frequency (ETSI CAM) from table 5.2

5.5.3 ETSI DCC parameters

In the first part of experiments described in section 5.3.1, the reactive FSM that we use has 3 states only (Relaxed, Active, and Restrictive). This is a standard FSM described in ETSI TS 102 687. The CBR_{target} is 0.6. The message generation rates are ETSI CAM, 2.5 Hz, 5 Hz, 10 Hz, and 20 Hz. Each vehicle transmits with full power. For the adaptive DCC, we still employ parameters from ETSI TS 102 687, which can be found in table 5.3. After that, the proposal in section 4.2 is applied.

It is important to discuss the CBR_{target} in the second experiment from section 5.3.2. After a series of trial simulations, even in a very high message frequency, the CBR cannot reach 0.6. Thus, just for testing, we lower the CBR_{target} to observe the effectiveness of the dynamic β scheme. The CBR_{target} we choose for the second experiment is listed in table 5.3.

Parameter	Values
α	0.016
β	dynamic
CBR_{target}: multi-lane platoons only	0.045
CBR_{target}: multi-lane platoons with individual vehicles	0.11

Table 5.3: **Parameters' values of the adaptive ETSI DCC**

Chapter 6

Results

6.1 Part 1: Evaluation of the proposal on ETSI DCC in a multi-lane platoon scenario.

In this section, we present the result of the first experiment from section 5.3.1. After applying the proposed modification to the ETSI DCC reactive on the multi-lane platoon scenario, we can considerably reduce the channel load which is demonstrated in figure 6.1. The same phenomenon occurs when we evaluate the modified adaptive ETSI DCC in figure 6.2. It can be noticed that in both approaches, the higher the load is, the more CBR the modification helps to reduce. For example, in the reactive approach, with the dynamic message rate (1.25 Hz), the reduced amount is not much, the same as what happens with the adaptive approach (approximately 0.02). However, at the highest load (message frequency is 20 Hz), the FSM-based witnesses 0.1 drops, and the linear approach observes a reduction of up to 0.22).

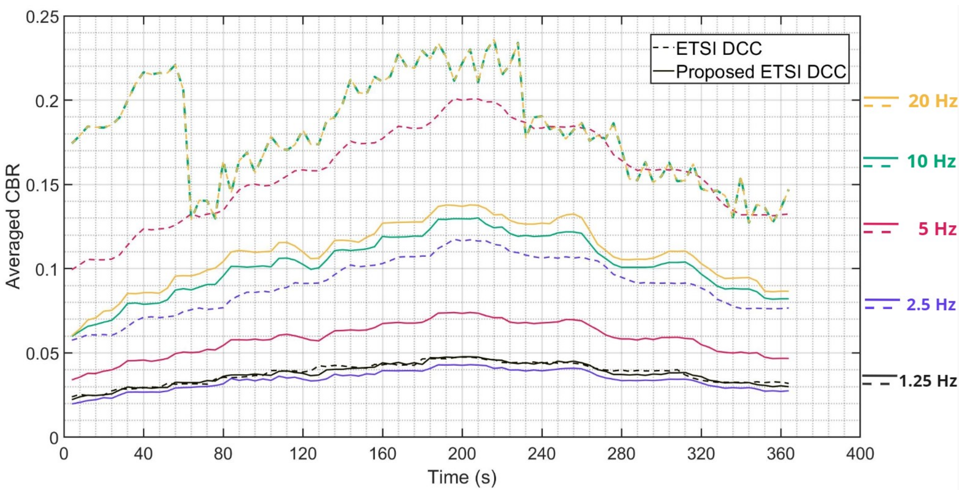

Figure 6.1: **Changes in CBR when applying modification for multi-lane platoons compared to CBR from the reactive ETSI DCC.**

It is also important to see the behavior change in the reactive DCC. As mentioned in section 3.2, the FSM-based approach has a drawback of oscillation in the CBR, especially when at a high load. Applying our proposal helps not only to reduce the CBR at the highest load but also to alleviate the oscillation phenomenon.

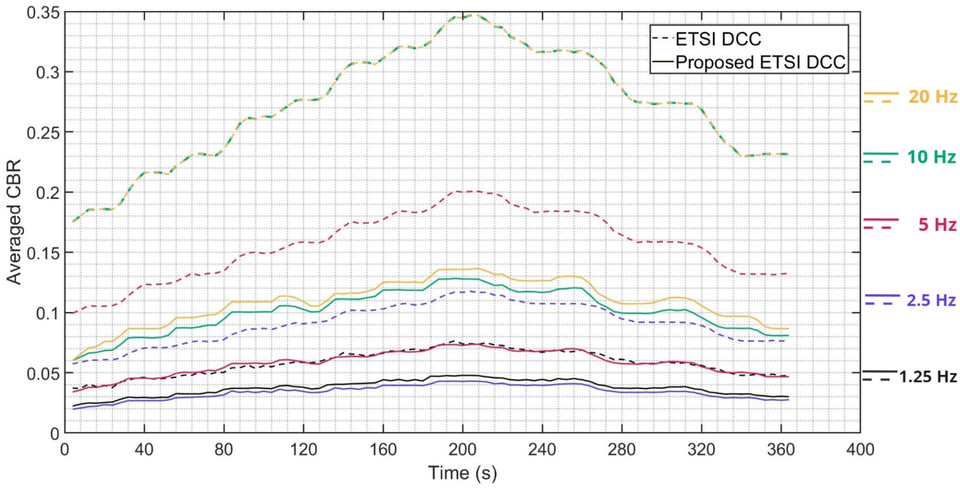

Figure 6.2: **Changes in CBR when applying modification for multi-lane platoons compared to CBR from the adaptive ETSI DCC.**

In figure 6.3, we can see the the effect of multi-lane platoon's modification on the delivery ratio. Regardless of either low or high load, the modification does not affect the delivery ratio, only 1 or 2 %. In other words, our changes do not compromise the performance of the original standard.

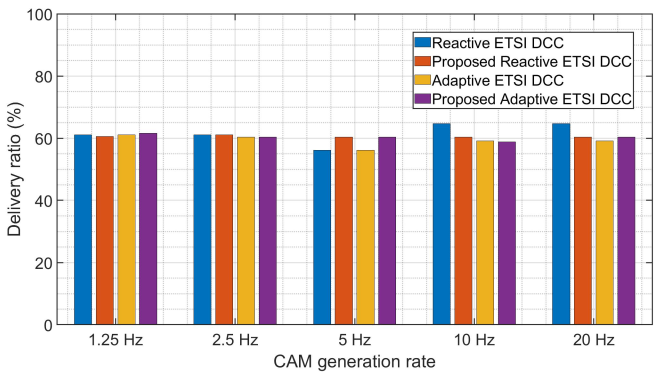

Figure 6.3: **Delivery ratio in the reactive and adaptive DCC when applying multi-lane platoon's modification in an increasing message frequency.**

More improvements are witnessed with the inter-message time, demonstrated in figure 6.4. We can see that in the dynamic rate (1.25 Hz), the inter-message time is improved by 37.5 %, from 800 ms to 500 ms. Other improvements are with 10 Hz and 20 Hz message frequencies when the adaptive approach witnesses 42.5% drops, from 174 ms to 100 ms. At other rates, we make the inter-message time remain unchanged.

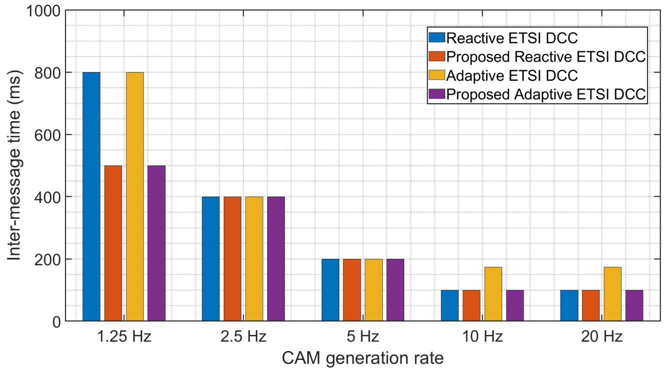

Figure 6.4: **Inter-message time in the reactive and adaptive DCC when applying multi-lane platoon's modification in an increasing message frequency.**

Unlike the delivery ratio from figure 6.3 and inter-message time from figure 6.4, the message age metric observes some unexpected changes displayed in figure 6.6. First of all, a significant change occurs with the dynamic rate (1.25 Hz) when a 98% drop is seen. The message frequencies of 2.5 Hz and 20 Hz also see considerable drops from 30.7% in the former and 74.3% in the adaptive DCC of the latter. However, at 5 Hz and 10 Hz, the results are much worse, especially with the 5 Hz. An increase of 300% at 5 Hz is significant. That is why we decide to extend our work to do follow-up experiments. Our next step is to keep the message frequencies of the member and increase that of the platoon leaders and lane leaders. To be specific, the new set of frequency pairs and the CAM age results are presented in table 6.1. As we can see, CAM ages are improved in those follow-up experiments.

Table 6.1: **CAM age comparison**

Message frequency (Hz)	CAM age (ms)
PL/LL: 5 & M: 2.5	75.3
PL/LL: 5 & M: 5	21
PL/LL: 10 & M: 2.5	3
PL/LL: 20 & M: 2.5	3
PL/LL: 10 & M: 5	97.2
PL/LL: 10 & M: 10	72
PL/LL: 20 & M: 5	80

Even better, we witness a rise in CBR in the follow-up experiments from the one with our proposal and still lower than CBR in the original ETSI DCC. An example is shown in figure 6.5.

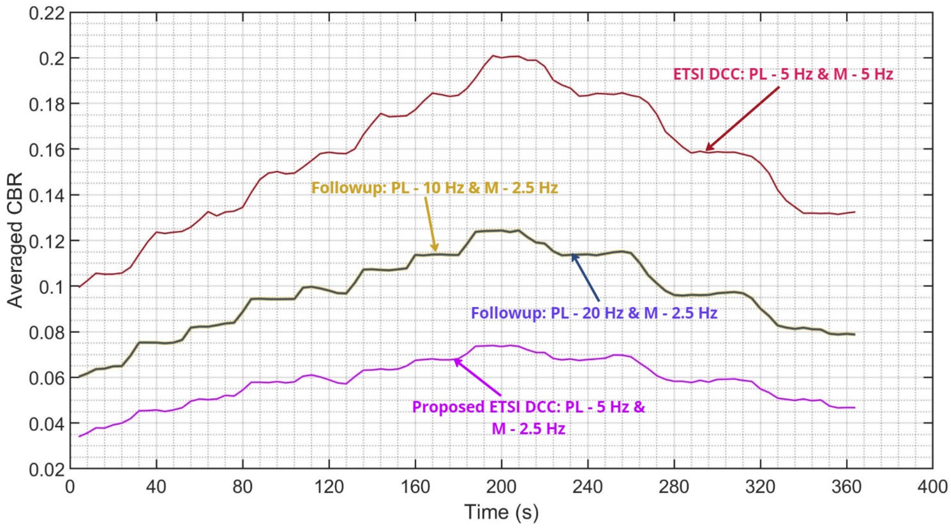

Figure 6.5: **CBR in a follow-up experiment between the original ETSI, the proposed ETSI's modification, and follow-up configurations.**

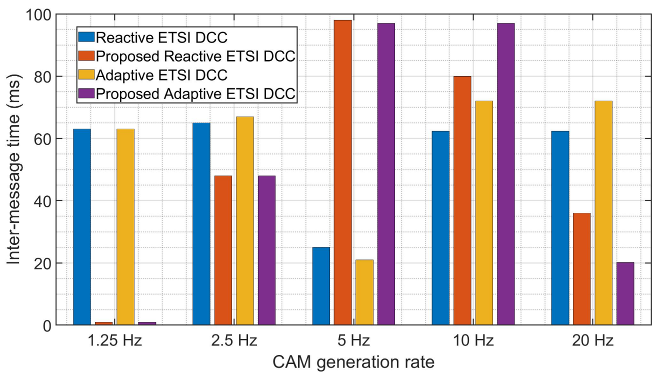

Figure 6.6: **CAM age in the reactive and adaptive DCC when applying multi-lane platoon's modification in an increasing message frequency.**

At this stage, we see an opportunity in expending these follow-up experiments to find out which pairs of message frequencies produce a CAM-age satisfactory. Thus based on table 6.1 and table 5.2, we try to vary those of platoon leaders and lane leaders such that they are larger than at least double the rate of platoon members which is fixed. The end result of recommended pairs is displayed in table 6.2. it is important to remind that these pairs are just experimental results.

Table 6.2: **Experimental frequency pairs between PL/LL and M that satisfy CAM age requirement**

PL/LL	M
2 → 5 Hz	1.25 Hz
10 Hz	1.25 → 4 Hz
20 Hz	1.25 → 4 Hz, 10 Hz

6.2 Part 2: Experiment on the dynamic β

In this section, we present the result of the second experiment from section 5.3.2 which includes results in the uniform traffic and in the mixed traffic.

6.2.1 Uniform traffic: multi-lane platoons only

The performance of the dynamic β is presented in figure 6.7, in terms of the behavior of CBR. Besides a little exceed over the target, it can be seen that our busy rate is much closer to the CBR_{target} compared to the CBR of the default β. The increasing phase from the beginning to the 80^{th} second is when all the platoons appear in the scenario. When all the vehicles are in the simulation, we have a region of interest which is the red rectangle in figure 6.7. In this region, we can see the averaged values of all the metrics from section 5.4 and delta (the allocated time portion each node is allowed to transmit) are improved and some of them are significant. The table 6.3 presents these improvements. We can see the greatest improvement is on delta which is up to 365%, meaning that a node has more time to transmit.

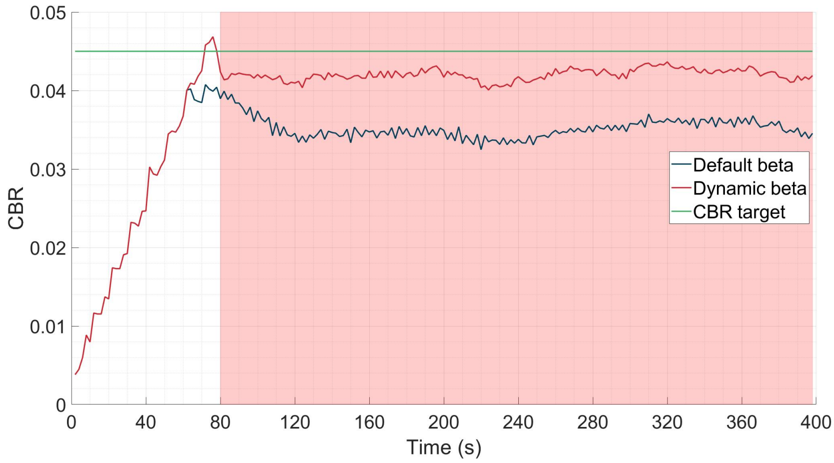

Figure 6.7: **Channel load when dynamic β is applied, compared with that when using default β from ETSI DCC, in the scenario with multi-lane platoons only**

Metrics	Default β	Dynamic β	Changes
Delivery ratio	72%	88%	22.2%
Delta	0.000741	0.003445	365%
Message age	0.712 ms	0.197 ms	72%
Inter-message time	692 ms	563 ms	18.6%

Table 6.3: **Uniform traffic: Improvements in metrics when applying dynamic β compared with those from default β.**

6.2.2 Mixed traffic: multi-lane platoons with individual vehicles.

The results of a more complex situation are presented in this section. First of all, we can see the behavior of CBR, demonstrated in figure 6.8, when there is interference from another group with a high load. We can observe the change in the number of vehicles in the additional notes along the x-axis.

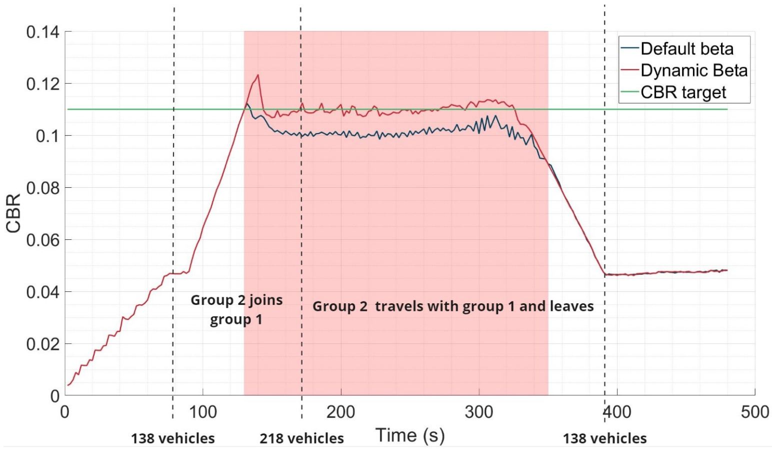

Figure 6.8: **Channel load when dynamic β is applied, compared with that when using default β from ETSI DCC, in the scenario with multi-lane platoons and single vehicles**

The attention is on the red rectangle as the region of interest. In general, the channel load of dynamic β fluctuates around the target while the default β is further from the target. Although there is a spike over the target at around the 130^{th} second, the average result is still better than what is achieved with the ETSI DCC standard.

This claim is once again reinforced by the table 6.4 showing other metrics in this experiment. Similar to the results of metrics in the uniform scenario, the delta witnesses the highest and most significant improvement of 310%. However, the other three metrics only improve a little.

Metrics	Default β	Dynamic β	Changes
Delivery ratio	81%	90.3%	11.5%
Delta	0.00095	0.0038	310%
Message age	0.560 ms	0.544 ms	2.8%
Inter-message time	640 ms	590 ms	7.8%

Table 6.4: **Improvements in metrics when applying dynamic β compared with those from default β.**

Chapter 7

Discussion

From what is presented in chapter 6, there are several things that need to be discussed.

To begin, in the first experiment for both the reactive and adaptive DCC, we see a drop in CBR when applying our proposed modification for multi-lane platoons, instead of using the default standard. It might not be considerable at the dynamic message rate (the lowest rate) since the drop is not much (0.2% in the adaptive approach and almost nothing different in the reactive one). However, when increasing the message frequency which means the load also increases, more CBR is reduced, especially the highest at the most intense load. This result brings two benefits.

First, the proposal prevents the possibility of channel congestion, especially in dense traffic. Thus, our proposal with the ETSI DCC enhances the functionality of congestion control and congestion prevention. Secondly, there is more room for communication activities, especially when the channel experiences a very high load. This is crucially important in some cases. For example, when there is a crowded scenario with a huge number of vehicles causing congestion, an additional load from an ambulance or VIP vehicle desperately needs a portion of the channel. This is the case where the proposal improves the situation and it can happen regularly.

Another case that benefits from such a drop is the crowded scenario. When a highway has a huge number of vehicles stopping at a traffic light, the congestion control might need to work really hard and effectively to put everything under control. That is why if those vehicles can temporarily group into multi-lane platoons, the channel relieves significantly from the huge load in this case.

Although we manage to reduce the channel load in different message frequencies, the proposal does not compromise the performance of each vehicle. This can be observed in figure 6.6, figure 6.3, and figure 6.4. Even better, for some metrics at some frequencies, the results are improved. Only in CAM age at 5 Hz and at 10 Hz, the performances are worse. However, this brings a chance to further evaluate different pairs of message frequencies which are mentioned in the follow-up experiments. Furthermore, the follow-up experiments offer us a chance to further test the idea of limiting one's room to prioritize others'.

In the second experiment, for both uniform and mixed traffic we can see that the dynamic β performs better than the fixed β, in terms of metrics. The channel achieves higher utilization and the resources are more effectively used. This is done thanks to the dynamic values of β which are much closer and realistic to the ideal β, the inverse of the number of active nodes K.

It is very important to emphasize that our use of dynamic β might not be accurate to the realistic number of active nodes. First, the estimated K from the Location Table might be much less than the actual number of nodes until the Location Table is updated. However, the adaptive ETSI DCC is developed from LIMERIC which has an inequality as follows:

$$\alpha + \beta \times K < 2$$

This inequality ensures that convergence is guaranteed with a higher number, to a certain point, of vehicles than the estimated one. Secondly, the Location Table might estimate a higher number of vehicles than the actual number within one's range. This is possible since the current expiry time of an entry in the Location Table is 20 seconds. However, we believe that in such a case, the estimated number is still much closer to the actual one than 833.33 vehicles from the standard ETSI DCC. Despite such possibilities, in both mixed and uniform traffic, all the metrics are improved when using dynamic β.

Lastly, it is important to discuss a bit about fairness, which is one of the important criteria for the adaptive DCC or LIMERIC-based approaches. In theory, β is used to counter the effect of having a number of nodes in a scenario. It represents the portion each node, channel load contributors, needs to handle. Also, β contributes significantly to the calculation of δ. Thus, it is very possible that the series β values of a node might be different than those of other nodes. Consequently, δ experiences the same phenomenon. That is why on average, fairness might not be achieved when deploying dynamic β. In the long run, platoon members from different platoons might achieve fairness when all of them experience no change in the scenario, or in other words, a steady state.

Chapter 8

Conclusions and Future work

8.1 Conclusions

In this thesis, we uncover a number of challenges with conventional platoon formations, notably communication and traffic efficiency, especially in elongated platoons. To counter these challenges, we introduce a new approach: multi-lane platoons a temporary formation while moving. We specifically focus on the communication aspect of a multi-lane platoon.

To implement our concept, we establish regulations for communication links, transmit power, and message frequencies, prioritizing members based on their attributes. After that, we propose some modifications to the current European standard (ETSI DCC) to facilitate what is regulated. A series of comparisons are made based on a set of metrics. As a result, several benefits are achieved without compromising overall performance. They consolidate this work's significance. In addition, we execute a number of follow-up experiments in an attempt to improve worse results in CAM age, which leads to a suggestion on matching message rate pairs.

We also delve into the possibility of a cross-layer mechanism in providing an estimation of how many active nodes are contributing to the channel load. The motivation for this part stems from some disadvantages of using a fixed and low β from the standard adaptive ETSI DCC, which does not suit the multi-lane platoon scenario. Constructing two scenarios, we evaluate this new mechanism and compare it with the default β. The results manifest improved channel utilization and, more importantly, significant improvement across various metrics.

In closing, we discuss deeper into the meaning of our achievement in practical situations and evaluate some cases not mentioned in our experiments.

8.2 Future works

In this section, we present a list of promising topics that are developed from our work:

Justified way to determine message frequency: In our work, we start with a two-to-one ratio in message frequencies. This is based on the fact that PLs and LLs communicate both inside and outside their platoon while members also "talk" within their platoon. After extensive experiments, we suggest a table with corresponding frequencies for various members. However, this table is experimentally suggested. Thus, a justified way to determine these frequencies with contributions of various factors can more effectively improve the overall performance.

Density for multi-lane platoons: we start our simulation with little to no standard in defining the density for platoons, including multi-lane platoons. Thus, future works from both standardization bodies and researchers on platoon densities might enhance the proximity from simulation to real life.

Thorough effect evaluation on dynamic beta: We suggest dynamic β with the purpose to serve the scenario with multi-lane platoons. Yet, we believe that this mechanism can also be used in individual vehicles. However, other criteria such as fairness or oscillation are not considered. Thus, an extensive comparison with other β-related mechanisms and an exhaustive evaluation of the effect of dynamic β on other criteria need to be undertaken.

Grouping random vehicles to prevent congestion: As the results of our work in chapter 6, we can see how the CBR is reduced even in the highest load when we modify the ETSI DCC. This suggests a way to avoid congestion when the road is crowded. That is why one of the ways to resolve such a situation is to temporarily group a number of nearby vehicles and reduce the channel occupation.

A new type of message for multi-lane platoons: In our work, when considering a list of possible options in the ETSI DCC to establish a prioritization scheme, message priority based on the DCC profile is one of the possibilities. However, we do not employ such an option because we do not have a message type for multi-lane platoon communication. Using various types of messages with different DCC profiles was employed in the paper by Oscar Amando and his colleagues [3]. This approach already proved its effectiveness, which makes this topic possible.

Combinational effect of dynamic β and α: In our work, we only choose one value of α (0.0016) to experiment our proposal. As mentioned in section 4.3, this value of α provides a closer value to the CBR_{target} but has a slower convergence speed compared to α of 0.1. In addition, CBR from the second experiment (section 6.2) fluctuates around and sometimes exceeds the CBR_{target}. Those are the reason why further experiments on the other value of α might bring a different effect on the CBR's behavior.

Multi-channel communication: In our work, we equip only one transceiver for each node which must be tuned to the safety channel. When the transmit power of platoon members (not platoon leaders and lane leaders) is distance-based, we might deteriorate the hidden node problem. This is because platoon leaders and lane leaders from other platoons cannot sense other platoon members (not PLs and LLs). That is why employing more than one channel might benefit the delivery ratio when one channel can transmit with full power to announce its presence and the other channel does what we do in this work.

Expiry time in the Location Table: Last but not least, we want to further explore the possibility of changing the expiry time of each entry in the Location Table. Currently, the amount is 20 seconds. Besides, the Location Table is for multi-hop communication which can explain why the expiry time is that long. With one-hop communication, we might increase the accuracy of the estimated number of active nodes within one hop.

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