A Multi-Lane Platooning Paradigm with ETSI DCC

Huy Nguyen*, Suryansh Sharma*, R Venkatesha Prasad*, and Falko Dressler†
* Networked Systems Group, TU Delft, The Netherlands
† School of Electrical Engineering and Computer Science, TU Berlin, Germany

***Abstract*—Smart autonomous vehicles can cooperatively drive as platoons offering benefits like enhanced safety, traffic efficiency, and fuel conservation. While traditionally platoons have followed a single-lane, train-like structure they face challenges when scaling that include communication range limitations and lane-change difficulties. In this article, we propose a new paradigm of multi-lane platoons that spreads platoons across multiple lanes. We explore the characteristics of multi-lane platoons particularly focusing on communication parameters. Additionally, we propose a cross-layer mechanism to seamlessly integrate this concept within the existing communication standard, ETSI. Our work significantly enhances platoon communication performance in mixed traffic scenarios and we propose optimizations to improve its effectiveness.**

***Index Terms*—Multilane platoons, ETSI DCC, V2V communication, platooning, C-ITS, autonomous cars.**

I. INTRODUCTION

Advancements in autonomous vehicles and Cooperative Intelligent Transportation Systems (C-ITS) are propelled through innovations in sensors, communication, and control algorithms [1]. Smart vehicles now form platoons, offering benefits like fuel savings and enhanced traffic efficiency [2], [3]. Traditionally, platoons have followed a train-like structure with a lead vehicle regulating parameters for the entire group. Dedicated Short Range Communication (DSRC) facilitates inter- and intra-platoon messaging, but challenges arise with conventional platoon scaling, including communication range limitations and lane-change difficulties [4], [5]. To address these issues, proposals like L-platoon [6] and flexible platoon formations [7] have emerged, aiming to optimize communication and traffic flow. However, these approaches have limitations, particularly for establishing communication.

Recognizing these challenges, we propose a new paradigm of multi-lane platoons. By spreading platoons across multiple lanes, this concept offers increased flexibility, simplified communication, and enhanced observability. In this article, we explore the characteristics and limitations of multi-lane platoons, particularly focusing on communication parameters and the compatibility of ETSI's Decentralized Congestion Control (DCC). We evaluate DCC performance in mixed traffic scenarios and propose optimizations to improve its effectiveness.

II. ETSI DCC PRIMER AND RELATED WORK

ETSI has a provision of Decentralized Congestion Control (DCC) [8] which controls three parameters namely the Transmit Power (TP), the Transmit Rate (TR), and the Transmit Data-rate (TD). The status of the channel is indicated by the Channel Busy Rate (CBR) which is equal to the busy time (duration for which the received signal strength exceeds -85 dBm) over 100 ms [8]. Although ETSI DCC spreads across different network layers, we focus only on DCC_ACC [8] in the Access layer and DCC_NET [9] in the Network and Transport layer.

There are two approaches established by the standard to manage congestion: Reactive DCC and Adaptive DCC. Both of them were created to prevent the radio channel from being overloaded, as regulated by ETSI [10]. Reactive is a state-based mechanism, naming relaxed, active, and restrictive, to control transmission parameters. The state transition is periodically performed based on the evaluation of CBR which later is matched to a state's level of channel load. Besides the adaptive approach is a linear rate control mechanism controlling the transmission parameter by comparing the perceived CBR with the target CBR. The purposes of this development from the reactive approach are convergence to a desired channel value and fairness among neighboring vehicles and those vehicles that are in the same network. The control mechanism of Adaptive DCC is possible via α, the speed of convergence to the target channel load, and β, the representation of the share of the channel for each vehicle.

Several works have extended both the reactive as well as adaptive DCC approaches. One of the first approaches was to aggressively adapt the beacon interval [11]. Other works extend the number of reactive states to increase stability [12]. For the Adaptive DCC approach, the focus is to vary either α [13] or β [14] to achieve the optimal performance in different situations.

III. THE MULTI-LANE PLATOON PARADIGM

A platoon can be in either a single line or spread over many lines, which should regulate the role assignment of each platoon member. Firstly, we define a new role called Lane Leader (LL) which is assigned to the front-most vehicle in each lane. These act as the pseudo platoon leader for their respective sub-group of vehicles (in the same lane). Secondly, one of the LL vehicles is assigned the role of the Platoon Leader (PL). All other vehicles in the platoon are designated as Platoon Members (PM) as shown in Figure 1.

We split the communication in a multi-lane platoon into two: inter- and intra-platoon communication. For the former, only PLs, LLs, and non-platoon vehicles are allowed to talk with each other. PMs are not involved. Communication links within this domain have higher priorities over other links to prevent collision. On the other hand, intra-platoon communication includes links between PMs, LL, and PL. Each PM only

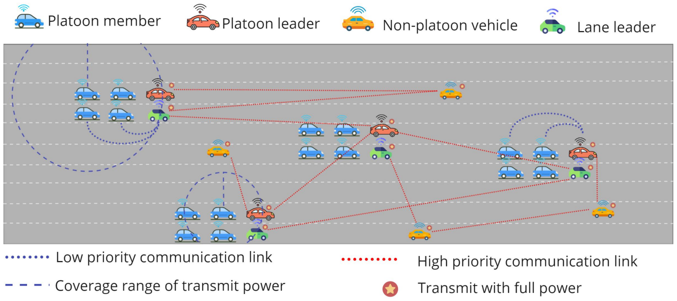

Figure 1: Role-based transmit power assignment of each vehicle in the platoon and their communication links.

communicates with its LL. Within this scheme, the LL-PL links have a higher priority over LL-PM links. High/low-priority assignment of each link type is based on the level of risk each vehicle bears. This hierarchy ensures the safety of the whole platoon and non-member vehicles on the road.

There are certain messaging constraints and requirements that are needed to ensure a smooth platoon operation which we define as follows: ❶ *Low age of information.* Each message (especially safety messages) should contain updated information about its sender with an emphasis on the links between lane leaders and platoon leaders ❷ *Adequate message periodicity.* A frequent link between the vehicles must be maintained, emphasizing the links between LLs and PLs which are regarded as high-priority members. ❸ *Adaptable transmit power.* The transmit power of the different vehicles in a platoon should be adaptable and based on the relative distances between a receiver and the sender, indicated by the exchanged update message of the geographical positions. This ensures that a communication link is maintained between the transmitter-receiver pair without overwhelming the channel for other vehicles.

IV. ENHANCING ETSI DCC FOR MULTI-LANE PLATOONS

We propose how to set the transmit power and transmit rate DCC parameters to establish priorities of different communication links. These parameters are set based on the roles assigned in our multi-lane platoon paradigm. We also explore how we can modify ETSI's adaptive DCC to work with platoons spanning multiple lanes.

Setting the transmit power. While traveling on the road, a platoon can exhibit various transient formations that last for a certain amount of time. During such a temporary formation, each member can presumably obtain the relative distances between itself and other members. Using additional information about the propagation model, the receiver sensitivity, and the relative distance between the intended transmitter and receiver, any platoon member can calculate the optimum transmission power. Thus, different vehicles can have different transmit power levels during any formation. These various levels are based on the level of importance of communication within the multi-lane platoon. We set full transmit power for platoon leaders, lane leaders, and any non-platoon vehicles on the road. All other members use a distance-based model system for setting their transmit power. The example of the coverage range of each vehicle is shown in Figure 1.

Setting the transmit rate. The second way to set priorities in multi-lane platoon communication is via the safety message generation rate. The front-most vehicles of a platoon possess a higher risk of message collision because they have more communication exchanges with other platoons as well as with non-platoon vehicles. Thus, besides the responsibility of broadcasting safety messages to vehicles outside their platoon, lane leader(s) and platoon leader must also communicate with each other and with the cars in their lanes. The lane leader(s), platoon leader(s), and non-platoon vehicles need to all broadcast messages at a rate higher than that of platoon members to ensure safety on the road for all vehicles. For preliminary testing, we set this message generation (and transmission) rate of the platoon leader/lane leader(s) to be twice as high as that of other platoon members.

Setting a dynamic β. We consider two multi-lane scenarios for which we can optimize the adaptive DCC: (a) homogeneous multiple multi-lane platoons on the road and (b) mixed traffic scenario (containing both multiple multi-lane platoons and non-platoon vehicles). For homogeneous traffic, the value of β can be easily set by increasing the ETSI DCC recommended value by 2 or 3 folds (0.0036, for example). This means the number of transceivers perceived by each vehicle reduces since fewer nodes participate in the global communication environment. Mixed traffic is a more realistic situation with a mix between single non-platoon vehicles and multi-lane platoons. In this case, the number of active users is unknown since there is no direct method of knowing the global number of non-platoon vehicles. We focus on only optimizing the adaptive DCC parameter β since this is related directly to the number of active communicating vehicles in the system.

Adaptive ETSI DCC efficiency issue. β is based on the difference between the current channel load and the target channel load. In theory, the value of β should be set as the inverse of the number of active nodes sharing the same wireless medium. Estimating the number of active nodes is not possible in the DCC access layer. According to the current standard, β is set at 0.0012 which is equivalent to 833.33 vehicles on the road and has a convergence guarantee of up to 1653.33 vehicles. However, when putting this value into a multi-lane scenario, a fixed value of β creates a slow convergence and update rate. In a dynamic situation that requires a fast response, this might not ensure safety. Setting β to 0.0012 underutilizes the channel for a longer time, wasting channel resources. In contrast, our approach utilizes cross-layer cooperation. Using the information from the Location Table (LT) in the Networking and Transport layer, the DCC access layer can calculate the value of β for the adaptive ETSI DCC mechanism. 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 this, DCC_ACC can set β dynamically.

Setting the β value dynamically using our approach has a caveat. The LT can also store information of multi-hop links along with single-hop nodes. We consider only one-hop communication links and thus, can estimate the value of K (the number of active nodes contributing to the channel load) more precisely. In a worst-case scenario, where entries in the Location Table do include multi-hop nodes, our method of estimation is still better than having a fixed β in the adaptive ETSI DCC. In case the estimated K (based on the number of entries in the LT) is not lower than the actual value, there is still room in the adaptive ETSI DCC for accommodating such a difference. This is because the adaptive ETSI DCC is developed from LIMERIC in which convergence is guaranteed up to a number based on the following inequality: $\alpha + \beta K < 2$. Thus, in either case, what we propose is still better than using a fixed β.

V. Evaluation and Results

We use the Artery simulation framework [15] with the Vanetza module that supports ETSI ITS-G5, the European standard of DSRC and includes all DCC features. We consider the road to be a highway with no obstacles around and use a Free Space Path Loss (FSPL) propagation model. We set the receiver sensitivity to -85 dBm as specified by the ETSI DCC standard. The amount of transmit power of each node is calculated as the sum of the FSPL and the receiver sensitivity. We start with the theoretical values of transmit power and then experimentally configure the amount to meet the demand. We use dynamic message generation frequencies of 2.5, 5, 10, and 20 Hz, which are commonly used to stress the channel. These message frequencies are used by non-platoon vehicles, PLs, and LLs. For PMs, we reduce these figures by half because PLs and LLs communicate both within and outside their platoons while PMs only communicate within. One thing to note is that by using the dynamic message frequency instead of a fixed one, we set the upper bound of the frequency of PLs, PMs, and non-platoon vehicles to be half of the ETSI standard. For the reactive DCC, we employ the FSM from the Artery framework and for adaptive DCC, we use the parameters from the document ETSI TS 102 687 [8]. We set the value of CBR_{target} to 0.6-0.7 which is widely accepted in literature [16]. When evaluating a dynamic β, we lower the CBR_{target} to observe the behavior of our optimization to 0.045 (homogeneous scenario) and to 0.11 (mixed scenario). We split the evaluation into two parts; **Evaluation of our enhanced ETSI DCC.** The focus is to compare the results of our modified DCC (we set the transmit power and message generation rate) to a baseline DCC. We consider the scenario of a highway with 6 lanes with a stream of 2-lane platoons that are 50 m apart from each other. In total, there are 138 vehicles organized into 23 platoons with an inter-vehicle distance of 5 m. After applying our modifications to the reactive ETSI DCC, we observe a considerable reduction in the channel load as seen in Figure 2. It is also essential to know the change in behavior for the reactive DCC. The FSM-based approach has the drawback of oscillating CBR, especially at high loads. After our modifications, we not only reduce the CBR at the highest load but we also alleviate the oscillation phenomenon. Similar improvements are also achieved for the modified version of adaptive ETSI DCC seen in Figure 2. For both DCC approaches, the higher the channel load, the more CBR reduction is achieved by our modification.

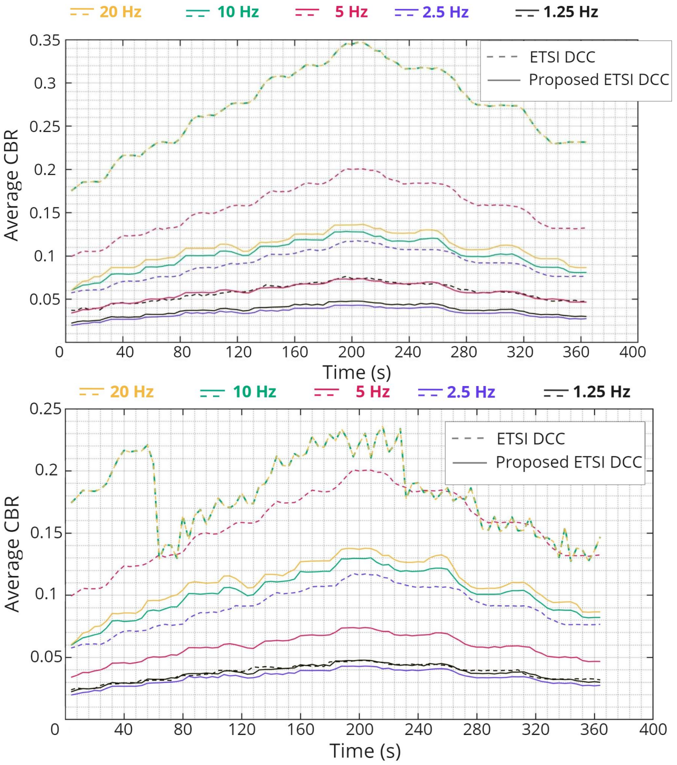

Figure 2: The behavior of CBR with our modifications for Adaptive (top) and Reactive (bottom) ETSI DCC.

Evaluation of setting a dynamic β. We test the performance enhancement when employing the dynamic β mechanism comparing it with the default static β in a multi-lane platoon. We evaluate the performance for two types of traffic: homogeneous traffic (multi-lane platoons only) and mixed traffic (multi-lane platoons and individual non-platoon vehicles together). For homogeneous traffic, the simulation setting is similar as before. However, for mixed traffic, we have an additional 80 non-platoon vehicles (Group-2) along with the 23 multi-lane platoons (Group-1). In this setting, the highway contains 10 lanes: 6 lanes for Group-1 and 4 lanes for Group-2. These non-platoon vehicles travel close to each other to create robust interference to the different platoons. Group-1 travels in its lane until the CBR is stable. Then, Group-2 enters the scenario, interfering with Group-1. After a while, Group-2 exits the scenario.

For the homogeneous traffic scenario, the performance of the dynamic β in terms of the behavior of CBR is presented in Figure 3 (top). Besides exceeding the target by a small margin, it can be noted that our channel busy rate is much closer to the CBR_{target} when compared to the default β. The rising trend observed from the start-up to the 80^{th} second is when all the platoons appear in the scenario. When all the vehicles are in the simulation, The region of interest is highlighted in red

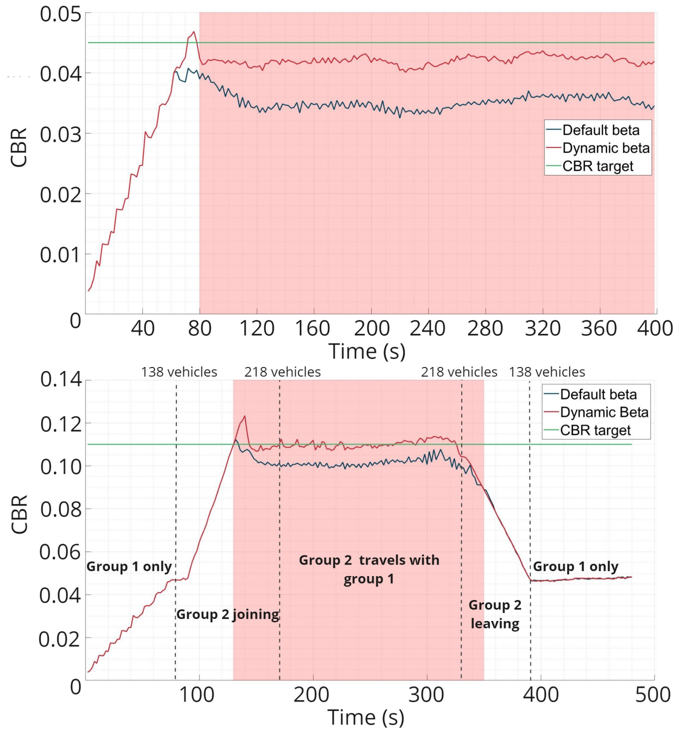

Figure 3: Behavior of CBR for dynamic β and the default static β for Homogeneous (top) and Mixed traffic (bottom) scenarios.

Table I: The effect of dynamic β on communication metrics.

Metrics	Homogeneous traffic			Mixed traffic		
	Default β	Dynamic β	Δ	Default β	Dynamic β	Δ
Delta	0.000741	0.003445	365%	0.00095	0.0038	310%
Delivery ratio	72%	88%	22.2%	81%	90.3%	11.5%
Message age	0.712 ms	0.197 ms	72%	0.560 ms	0.544 ms	2.8%
Inter message time	692 ms	563 ms	18.6%	640 ms	590 ms	7.8%

where we can see that the averaged values of all metrics and δ (the allocated time portion each node is allowed to transmit) are improved. Table I presents the significant improvements. We can see that delta has the maximum increase 365%, meaning that each vehicle gets more channel time to transmit. We can see the behavior of CBR for the mixed traffic scenario in Figure 3 (bottom) when there is interference from non-platoon vehicles.

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 130th second, the average result is still overall better than what is achieved using the ETSI DCC standard. This claim is once again reinforced by Table I showing other metrics from this simulation. Similar to the homogeneous traffic scenario results, the most significant improvement of 310% is achieved for δ. The other three metrics only show a little improvement.

VI. CONCLUSION

Multi-lane platoons represent a new way of organizing autonomous or semi-autonomous vehicles on the road and are especially relevant in large highways where such formations can benefit from the multiple parallel lanes. There is a need to have effective congestion control to not overwhelm the wireless channel and cause a safety risk due to the lack of timely and effective messaging. To this extent, our proposed paradigm makes a case for how such formations can be envisaged. Our proposal to the ETSI DCC can considerably reduce the maximum CBR in the system, especially when the message frequency is high, producing a high load. A new set of regulations in communication parameters, role assignment, and cross-layer cooperation is proposed to adapt and enhance the new concept in the context of ETSI. The proposal offers various benefits in congestion control and inter-vehicle communication efficiency.

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