A Comparison of Decentralized Congestion Control Algorithms for Multiplatooning Communications

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***Abstract*—To improve traffic safety, many Cooperative Intelligent Transportation Systems (C-ITS) applications rely on exchange of periodic safety messages between vehicles. However, as the number of connected vehicles increases, control of channel congestion becomes a bottleneck for achieving high throughput. Without a suitable congestion control method, safety critical messages such as Cooperative Awareness Messages (CAMs) may not be delivered on time in high vehicle density scenarios that can lead to dangerous situations which can threaten people's health or even life. The Decentralized Congestion Control (DCC) algorithm defined by European Telecommunications Standards Institute (ETSI), becomes a vital component of C-ITS applications to keep channel load under control and below a predefined threshold level. In this paper, we aim to analyze and evaluate the performance of a number of DCC protocols including ETSI DCC by providing a comparison between them for the multiplatooning application by using several widely-used evaluation metrics.**

I. INTRODUCTION

Recently, many research and efforts have been carried out towards concepts such as Vehicular Ad Hoc Networks (VANETs), Cooperative Intelligent Transport Systems (C-ITS) and their implementations, to improve driving safety, comfort and also traffic efficiency. Despite of all achieved advances in this domain, there are still some challenges that need to be addressed. As an example, traffic safety applications, such as platooning and Cooperative Adaptive Cruise Control (CACC) face difficulties in terms of communication that need to be addressed on a protocol design level [1]. In other words, to ensure safety of vehicular networks, beacon messages are periodically exchanged between road users, which includes information such as neighboring vehicles position, speed, driving kinematics and other attributes. However, by increasing the number of vehicles, the network may become congested.

A number of standardization organizations have indeed participated in the last decade to develop standards for vehicular communications, including among others the ISO at international level, the IEEE and the SAE in North America, the ETSI and the CEN in Europe, and the ARIB in Japan. ETSI has specified a profile of IEEE 802.11p adapted to the 30 MHz frequency spectrum divided into three channels at the 5.9 GHz band allocated in Europe that includes one control channel and two service channels. IEEE 802.11p, now part of IEEE 802.11-2012 [2], amended the IEEE 802.11 standard for the specific case of V2X communications. Like all 802.11 parts, it defines the protocols at the physical (PHY) and medium access control (MAC) layers. In Europe, it has been adopted under the name ITS-G5 [3], and here, we generally use IEEE 802.11p to identify both of them. At the PHY layer, IEEE 802.11p is very similar to IEEE 802.11a [4], as it uses Orthogonal Frequency-Division Multiplexing (OFDM). To prevent packet collisions, IEEE 802.11p uses carrier sense multiple access with collision avoidance (CSMA/CA) MAC protocols mechanisms such as listen-before-talk and back-off. But still the possibility of packet collisions exists which may lead to unlimited delays in channel access, specifically under heavy channel load conditions [5], [6], [7].

Two main types of messages exchanged in the context of safety applications are messages that includes status update and event triggered hazard warnings. In this context, ETSI has defined Cooperative Awareness Messages (CAMs) [8] and event-triggered Decentralized Environmental Notification Messages (DENMs) [9]. CAM includes updates about a vehicle's position and speed, or other in-vehicle sensor data and DENMs are triggered by unforeseen data. Before September 2014, the applied strategy for CAM generation was according to a periodic manner, but after that and according to ETSI EN 302 637-2, CAM messages are triggered based on vehicle movements. In order to provide reliable and timely exchange of CAMs, it is required to keep channel congestion under control [10]. In other words, C-ITS communications must be operational in dense road traffic, so congestion control is required to avoid reduction in system performance, provide a fair access to channel resources among neighboring ITS-G5 stations and avoid packet collision, packet loss and packet delay. In this context, the Decentralized Congestion Control (DCC) framework, shown in Figure 1, specified by ETSI can be applied. It allows C-ITS nodes to keep channel load below a target threshold by adopting transmission parameters. In this paper, we analyze and evaluate the performance and effectiveness of both standard and non-standard DCC protocols for the multiplatooning application with different number of platoons by using different evaluation metrics which allows us to draw a more comprehensive conclusion.

The rest of this paper is organized as follow: Section II describes background and the state of the art for papers related to DCC. In Section III, we provide our simulation details including simulation scenario and evaluation metrics. In Section IV, we present the result of our simulation and analysis. Finally, Section V contains the discussions and conclusions.

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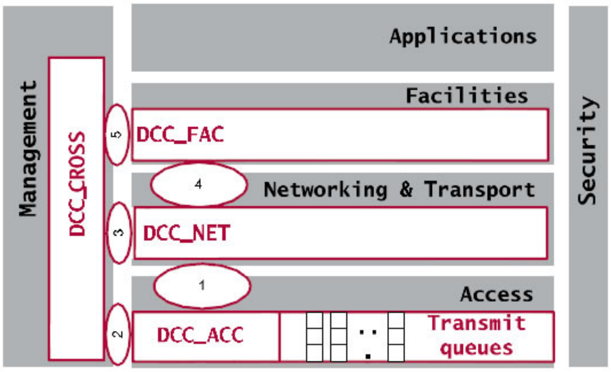


Fig. 1. DCC Architecture [11]

II. BACKGROUND AND STATE OF THE ART

Several studies have discussed different approaches to overcome congestion control problems. In this section, first we briefly explain the DCC standard method by ETSI. Then, we present the papers that evaluate the performance of the current ETSI DCC standard and discuss their limitations such as fairness, stability and reliability. Also, we investigate the papers that provide modifications on ETSI DCC standard, and finally we will go through the papers that present other alternatives for congestion control in decentralized vehicular environments.

DCC is based on a three state machine (Relax, Active and Restrictive) and thus is calld DCC-3. Any changes in state of machine are based on an evaluation metric called Channel Busy Ratio (CBR) [12], as shown in Figure 2. To control the vehicles channel access, different mechanisms such as Transmit Power Control (TPC), Transmit Rate Control (TRC), Transmit Data rate Control (TDC), DCC Sensitivity Control (DSC), and Transmit Access Control (TAC) are considered [11]. However, keeping channel load below a target threshold disturbs reliability and timing requirements of safety applications. In addition, DCC-3 suffers from unfairness and instability problems as a result of dramatic parameter changes between states.

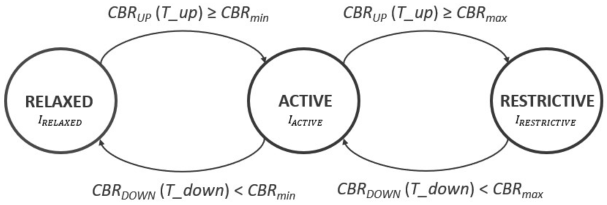


Fig. 2. DCC-3 state machine

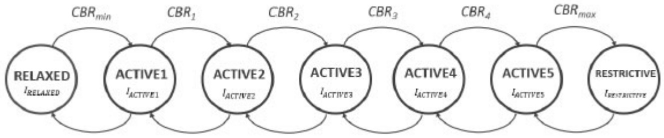


Fig. 3. DCC-7 state machine

In [13], Kuk et al. used simulation and real experiments to evaluate the performance of ETSI DCC. According to their findings, by inappropriate configuration of DCC parameter values, safety messages are unable to reach beyond immediate adjacent neighbors, when vehicles enter the RESTRICTIVE state (even in non-congested conditions). Gunther et al. [14] performed simulations based on Artery framework. This framework provides vehicle to everything (V2X) simulations based on ETSI ITS-G5 protocols. They showed that channel resources are not used efficiently by current DCC which cause challenges for channel load. Other DCC problems such as stability and fairness were shown in [15] and [16]. Yang and Kim also discussed in [17] that various parameter changes among different states causes instability and unfairness problems. As a result, they proposed simple DCC (SDCC), which has two more states based on TDC and they showed the performance is improved comparing to ETSI DCC in terms of stability and fairness. In [18], Autolitano et al. used simulation experiments to evaluate the performance of DCC. According to their results, adopting parameters, such as TRC and TPC affects the general behavior of DCC. In addition, a more efficient approach rather than binary channel load measurement should be applied.

The second group of papers are those provide modifications to the standard. To increase vehicle awareness, Aygun et al. [19] combined transmit power with rate control by proposing an Environment and Context-aware Combined Power and Rate Distributed Congestion Control (ECPR). This can be simply built upon current DCC. As mentioned before, current ETSI DCC suffers from stability and reliability problems. To improve this, Subramanian et al. [20] proposed a TDM (Time-Division Multiplexing) overlay on top of the IEEE 802.11p MAC layer to increase the rate of correctly received packets (RCRP) by injecting packets in synchronized time slot. The results showed that synchronous algorithms outperforms asynchronous one in terms of stability and reliability. To improve Packet Reception Rate (PRR) and latency, Torrent-Moreno et al. [21] proposed a method which ensures messages with high priority have enough bandwidth by using TPC.

Apart from ETSI DCC-based methods, some researchers presented other alternative solutions for congestion control. Zheyuan [22] applied DCC with more sub-states in ACTIVE state based on TRC and evaluated the performance of DCC based on CBR, velocity synchronization and acceleration synchronization. According to their results, the performance of DCC with more sub-states in ACTIVE state is better than three state DCC. Lyamin et al. [23] proved that this can also reduce fuel consumption. In this paper, we implemented DCC with five sub-states in ACTIVE state based on ETSI TR 101 613 standard [24] that will be called DCC-7 in the rest of the paper. As shown in Figure 3, the basic working principles of DCC-7 is similar to DCC-3.

Due to limited numbers of message generation intervals for all channel congestion conditions in DCC-3 and DCC-7, Sommer [25] presented a dynamic beaconing (DynB) protocol which the message generation interval is adopted dynamically based on channel load. The main intention is to maintain CBR at a fixed value to reduce packet collisions. This can be done through increasing the message generation interval whenever the network becomes denser. There are two control variables related to DynB: b_t, which is the fraction of busy time between $t - I$ and t and N, which is the count of one-hop neighbor. Using these two variables keeps I close to I_{des} (desired value) as far as channel load does not become bigger than b_{des} (desired value). Equation 1 can be used to calculate the message generation interval ($r = b_t/b_{des} - 1$):

$$I_j = I_{des}(1 + r_j * N_j) \tag{1}$$

According to their results, comparing mechanisms adopted by ETSI, namely TRC and also static period beaconing, DynB performs much better.

LInear MEssage Rate Integrated Control (LIMERIC) algorithm [26] adopts the message rate, to control the number of packets sent per second. LIMERIC is a distributed and adaptive linear control algorithm that vehicles can use to adapt their message rates to ensure that the total channel load converges to a desired target value. To adopt the message rate of j^{th} vehicle, equation 2 can be used:

$$R_j(t) = (1-\alpha)*R_j(t-T)+\beta*(CBR_T-CBR(t-T)) \tag{2}$$

α and β are convergence factors that impact stability, fairness and state convergence. $R_j(t - T)$ is the message generation rate and $CBR(t-T)$ is the measured CBR at $t-T$ (T is the message generation interval and CBR_T is the target channel load). LIMERIC provides high throughput, which is independent of the number of neighbor nodes.

However, there are only few papers [23], [25] that evaluated DCC mechanisms for multiplatooning application based on realistic simulation experiments and as the best of our knowledge, none of them showed a comprehensive evaluation, including different proposed methods by the research community and evaluation metrics.

III. SIMULATION DETAILS

A. Simulation Scenario

In our simulation study, we use PLEXE [27], which is an extension of VEINS simulator [28] - a combination of OMNeT++ [29] and SUMO simulators [30] - to support platooning applications. OMNeT++ is a discrete event-based simulator for simulating network communications, while SUMO is a traffic simulator which can support large traffic scenarios. As a result, PLEXE provides a comprehensive framework for vehicular communication. In our simulation setup, we created a 4-lane highway scenario using SUMO traffic simulator, as shown in Figure 4. Each lane is 3.2 m in width and 10 km in length. A summary of network simulation parameters and road traffic simulation parameters is provided in Table I.

TABLE I
ROAD TRAFFIC SIMULATION PARAMETERS.

Parameters	Values
Intra-vehicle distance	5 m
Inter-vehicle distance	33 m
Platoon size	8 vehicles
Platoon injection start time	1s
Vehicle length	4m
Vehicle speed	100 km/h
Vehicle max speed	110 km/h
Simulation duration	20 s

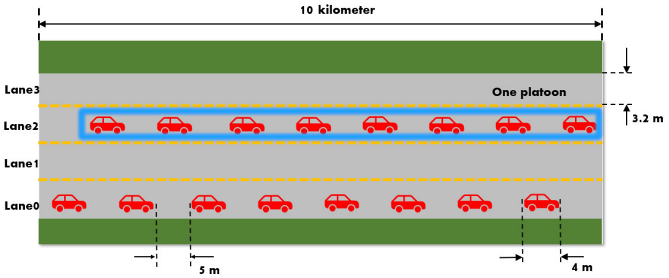


Fig. 4. The highway scenario setup in SUMO

B. Evaluation Metrics

The evaluation is based on four widely-used parameters as follows:

- Channel Busy Ratio (CBR): CBR is defined as the percentage of channel busy duration over the measurement interval. In this paper, since packet delivery ratio reaches its peak when CBR is around 0.6 to 0.7 [31], we set the desired CBR (CBR$_{des}$) to 0.7. We sample and record CBR values every 0.1 s.
- Inter-Reception Time (IRT): it is calculated as the time interval between the sequential reception of beacons from each member averaged over all platoon members [32]. The IRT parameter reflects the data age of the beacon content as it monitors the age of the information a node holds from a specific neighbor once a new beacon arrives.
- Fairness: We calculated fairness using jain index $(\Sigma_{i=1}^{n} x^i)^2/(n.\Sigma_{i=1}^{n} x_i^2)$ over the number of beacon messages delivered per transmitting vehicle per second [13].
- Safe Time Ratio: as provided in [33], safe time ratio is defined as equation 3 (D is the set of all message delays of a vehicle):

$$r_{safe} = \Sigma_{d_s \in D_{safe}} d_s / \Sigma_{d \in D} d \tag{3}$$

IV. SIMULATION RESULTS AND ANALYSIS

In this section, we benchmark DCC-3 against STB (no congestion control mechanism), DynB, LIMERIC, and DCC-7 using different evaluation metrics for the multiplatooning scenario showed in section III-A with different numbers of platoons.

A. CBR

The performance of different protocols to control channel load is displayed in Figure 5. From the viewpoint of STB

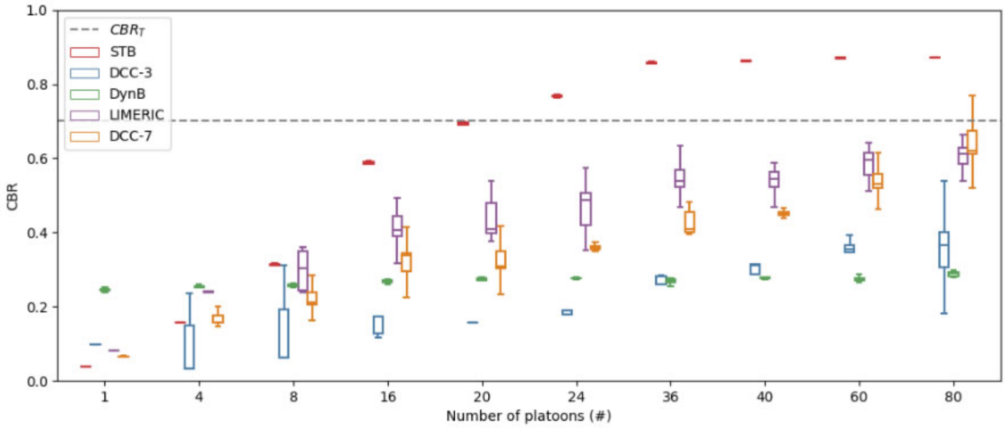


Fig. 5. Comparison of CBR for different algorithms with different number of platoons

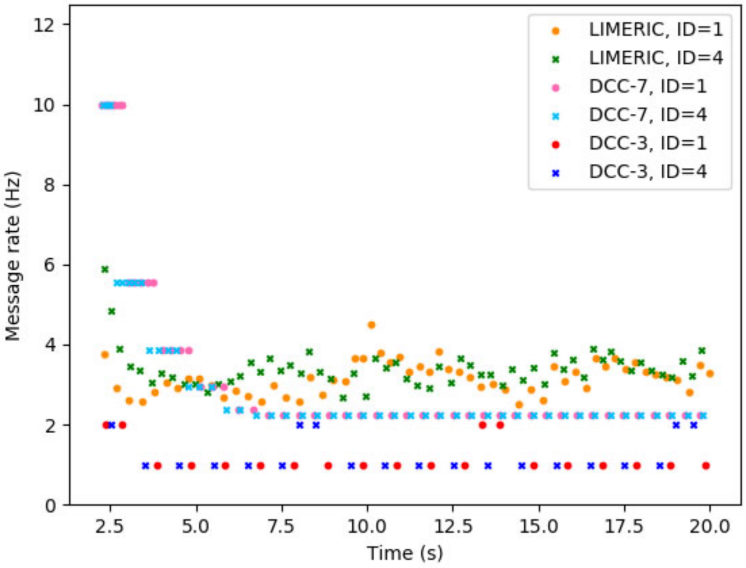


Fig. 6. Comparison of fairness for DCC-3, LIMERIC, and DCC-7

and with huge number of platoons, CBR values reach almost 0.9 which shows that STB is unable to keep channel load under control. The reason is that the message generation rate of STB is fixed to 10 Hz regardless of the channel congestion. In contrast, DCC-3 is able to keep CBR values under 0.55 even with large number of platoons, but the maximum CBR value is 55%, which is far from the CBR$_{des}$. DynB can dynamically adjust the message rate based on the channel load and maintains CBR at around 0.25, but with the cost of increasing the message generation interval. Next, it can be seen that LIMERIC is able to keep CBR values lower than 0.7, even with large number of platoons. In other words, LIMERIC dynamically adopts the message rate to target CBR at 0.7, while DCC-7 only has fixed message rates based on the state machine. So, we can conclude that generally, LIMERIC has the highest channel utilization comparing with STB, DCC-3, DynB, and DCC-7. In case of 80 platoons, channel utilization of DCC-7 is higher than LIMERIC.

B. Fairness

In our simulation, message rate for two nodes (vehicle 1 and 4) in the same platoon on Lane 1 with 80 platoons are observed. Figure 6 displays the scatter plot of the distribution of message rate as a function of simulation time. As shown, the convergence of message rate of LIMERIC is to similar values for different nodes over time. This is because LIMERIC adopts a vehicles message rate based on channel load, hence it tends to share channel resources in an evenly manner for all vehicles. For DCC-7, in the time interval of 6s to 20s, both nodes have almost similar message rates (2Hz) as there is shorter gaps between states in DCC-7 comparing to a three state machine. Therefore, we can conclude that comparing to DCC-3, LIMERIC has better performance in term of fairness,

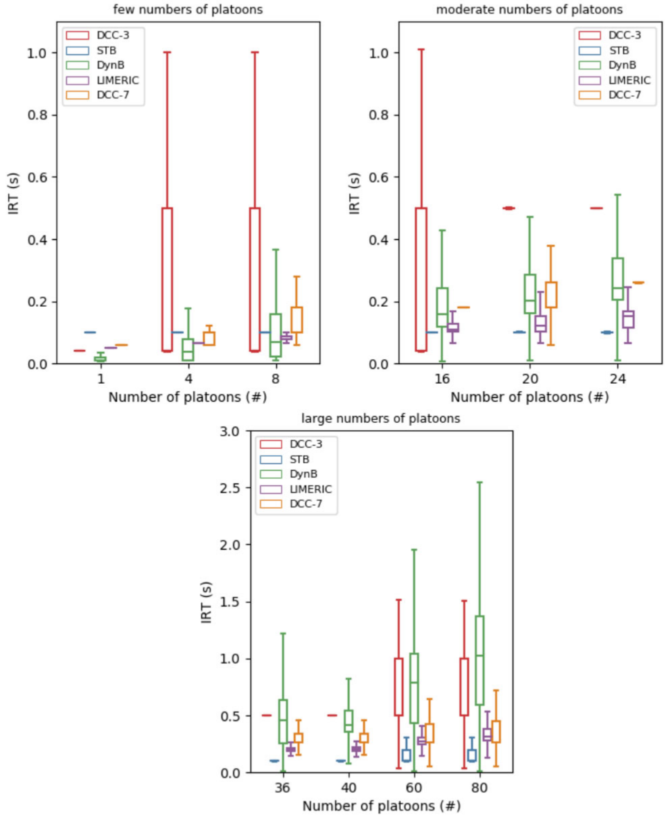


Fig. 7. Comparison of IRT for different protocols with different number of platoons

but DCC-7 outperforms both LIMERIC and DCC-3, as it provides the most stable division of the channel resources.

C. IRT

As provided in Figure 7 and Figure 8, IRT and message generation interval are analyzed through box plots, respectively. As shown in Figure 7, with few number of platoons (especially one platoon), STB has larger IRT values comparing with other protocols. This is because of the message generation interval which is the largest among others. With large number of platoons, IRT values reach almost 0.3s as the channel becomes almost congested. (shown in Figure 8).

For DynB and with platoons from one to eight, the maximum IRT values increase as the number of platoons increases. Generally, to keep channel load under control, IRT values of DynB increase as the message generation intervals increase. The maximum IRT value of DynB with 80 platoons exceeds 2.5s. As shown, the range of message generation rate for DCC-3 with four or eight platoons, represents packet loss because of packet collision and IRT values rise and fall irregularly. With large number of platoons, since the message generation interval is in the range of 0.5s to 1s, the IRT values of DCC-3 reaches 1.5s. For LIMERIC and with few number of platoons, the IRT values are always smaller than STB, due to smaller message generation interval. But with large number of platoons, IRT values of LIMERIC are larger than STB.

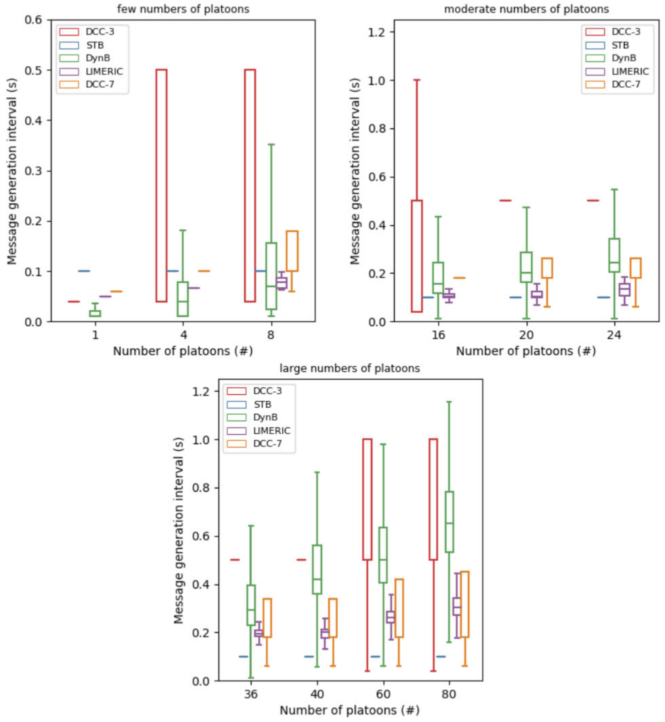
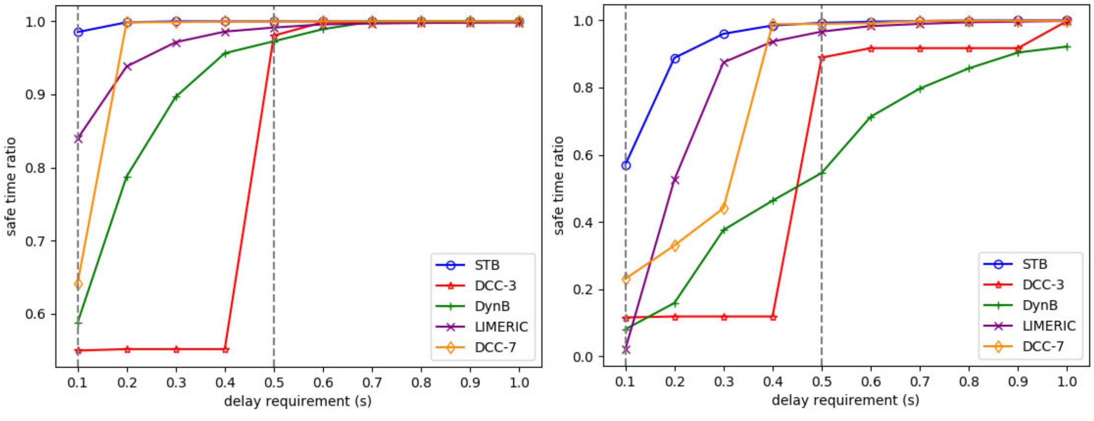


Fig. 8. Comparison of message generation interval for different algorithms with different number of platoons

The reason is that LIMERIC increase the message generation interval to target CBR at 0.7, but STB keeps a 10 Hz message rate regardless of channel load. Similar to DynB, IRT values of LIMERIC increase as message generation intervals increase to keep target channel load under control. In case of DCC-7 and with few number of platoons, the inter-quartile range in the box plots increases as the number of platoons increase. But because of parameter settings of state machine, the inter-quartile range of DCC-7 never exceeds DCC-3. Also, in Figure 7, it is shown that with large number of platoons, DCC-7 has larger ΔQ than LIMERIC because LIMERIC adapts message rate dynamically while DCC-7 only has fixed and limited message rates. So, we conclude that STB has the lowest values of of IRT in general, which is the result of fixed 10 Hz message generation rate and more importantly not an appropriate solution for large number of platoons. IRT value for DynB reaches almost 2.7s for large number of platoons and this may cause unreliability for real-time applications. Due to various changes among states, IRT values of DCC-3 has fluctuation and generally, DCC-7 and LIMERIC are able to control channel congestion.

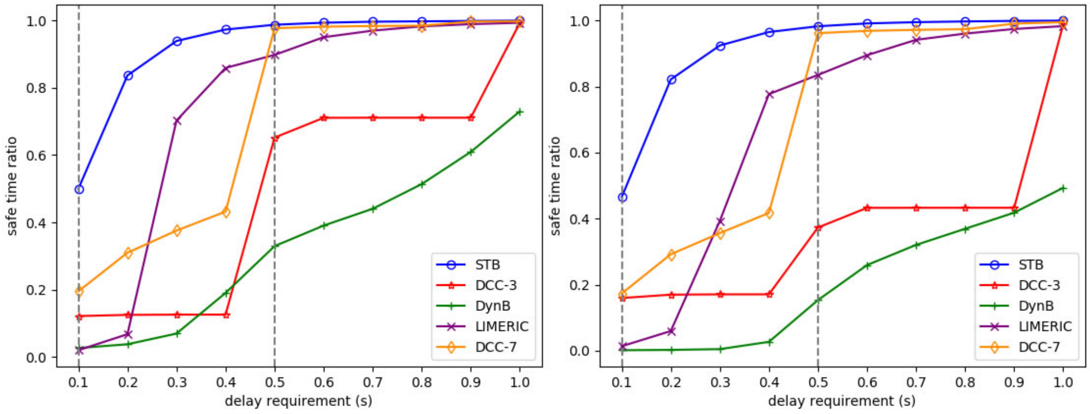
D. Safe Time Ratio

Figure 9 displays the results of the safe time ratio for different protocols with 8, 36, 60, and 80 number of platoons. As shown, with eight platoons and delay of 0.5s, all protocols can ensure the safe condition of platooning applications at almost 100% of the time. For 36 platoons and delay of 0.1s, the safe time ratio of all protocols excluding STB are generally



(a) safe time ratio for 8 platoons

(b) safe time ratio for 36 platoons



(c) safe time ratio for 60 platoons

(d) safe time ratio for 80 platoons

Fig. 9. Comparison of safe time ratio for different protocols with different numbers of platoons

below 0.2. Considering delay of 0.5s, DynB has almost 50% safe time ratio. In addition, as represented in Figure 9 (c), DCC-3 and DynB have almost 70% and 30% safe time ratio for δ_{req} of 0.5s, while DCC-7, STB, and LIMERIC have almost 100% safe time ratio for a delay requirement of 0.5s. Finally, for 80 platoons, DCC-3 and DynB only have almost 40% and 20% safe time ratio for a delay requirement of 0.5s. In contrast, DCC-7 and STB can still achieve almost 100% safe time ratio. So, we conclude that DCC-7, STB, and LIMERIC can achieve safe time ratio above 80% of the time for a delay requirement of 0.5s in our simulation scenario and even with large number of platoons. In the worst case scenario of a delay requirement equals to 0.1s, none of these protocols can achieve a safe time ratio higher than 80% with moderate or large numbers of platoons.

V. DISCUSSIONS AND CONCLUSIONS

In this paper, we showed a comprehensive evaluation of several decentralized congestion control methods, including DCC-3 (ETSI DCC), STB, DynB, LIMERIC, and DCC-7 by using different widely-used evaluation metrics, such as CBR, IRT, fairness and safe time ratio for multiplatooning application. Considering CBR, the highest channel utilization belongs to LIMERIC in most cases, comparing with STB, DCC-3, DynB, and DCC-7. In this context, although DCC-7 has a slightly lower channel utilization compared with LIMERIC, it greatly improves CBR compared with DCC-3. With respect to IRT, methods such as STB, DCC-3 and DynB have lowest performance comparing with DCC-7 and LIMERIC. We also conclude that the performance of DCC-7 in case of fairness is better than LIMERIC and DCC-3. This represents fair division of channel resources by DCC-7. Finally, from the viewpoint of safe time ratio, the results show that 80% of safe time ratio is achieved by STB, DCC-7 and LIMERIC, while DCC-3 and DynB perform unsafe for the platooning applications. In general, according to the simulation results, when considering CBR, IRT, fairness and safe time ratio, DCC-7 ouperforms the other methods, which were evaluated in this paper. In our future work, we will consider machine learning methods to train a model which can predict the link condition to neighboring vehicles to design an efficient congestion control method.

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