Enhancing ETSI DCC for Multi-Service Vehicular Safety Communication

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***Abstract*—ETSI Decentralized Congestion Control (DCC) for vehicular communication is an essential mechanism for limiting wireless channel congestion and resource allocation of ad-hoc V2X communications. Standardized channel congestion control protocols have been designed considering mostly a single message for cooperative awareness such as CAM/BSM, while future automated vehicles will exchange additional messages, including sensor data, control information, HD-maps etc.**

In this paper we evaluate and improve the performance of the state-machine based DCC standardized in Europe by ETSI. We highlight the channel capacity under-utilization and the communication quality degradation, and propose three design improvements to enhance its performance. Simulation based evaluation, considering multiple standardized safety messages on a single channel, proves the performance improvement due to our proposed modifications, almost doubling the reception throughput for dense V2X communication scenarios.

I. Introduction

Vehicle-to-Everything (V2X) communication will be soon ubiquitous on our roads to improve road safety and increase traffic efficiency by increasing a vehicle's awareness by communicating information beyond the driver's visual range and the vehicle's on-board sensors. Over the years, V2X networking protocols and communication technologies have been consolidated and is currently available for initial a.k.a Day 1 deployment. Two leading technologies have been developed for V2X communication, i.e. IEEE 802.11 based ITS-G5 in Europe/DSRC in the USA, and 3GPP Long-Term-Evolution (LTE) V2X. In IEEE 802.11 based vehicular networks and Mode 4 of LTE-V2X, there is no centralized channel resource allocator and the nodes need to prevent channel saturation by limiting the spatial and/or temporal channel usage through cooperative strategies.

Several wireless channel congestion control protocols have been proposed by the academia based on Transmit Rate Control (TRC) [1]–[3] and Transmit Power Control (TPC) [4], [5], while some protocols have been standardized for Day 1 deployment such as [6], [7]. In European standards developed by ETSI, TRC has been specified as the principle mechanism for congestion control at the Access layer [6], a.k.a Decentralized Congestion Control (DCC). Whether academia or standardization, the focus has been mainly to optimize channel usage while limiting Channel Load (CL) considering a single periodic broadcast message such as Cooperative Awareness Message (CAM) or Basic Safety Message (BSM).

In future or Day 2 scenarios, revolutionary V2X applications, such as highly automated driving (HAD) and safety of Vulnerable Road Users (VRU) will be based on a multitude of V2X services, such as Collective Perception (CP) [8] and Maneuver Coordination (MC) [9]. Several types of messages, such as CPM and MCM will be generated by such applications, which will strain the communication resources.

In this regard, ITS-G5 has been criticized for having insufficient capacity. However, previous studies [10]–[12] and ETSI Technical Report TR 103 562 [8] have demonstrated that the inefficient channel usage with regards to DCC is a problematic aspect of ITS-G5. Accordingly, complementary to developing multi-channel operations or new radio technologies to acquire more channel capacity, it is also critical to use the channel in the most efficient way.

In a previous study [10], we demonstrated the inefficiency of the initial version of DCC (v 1.1.1, 2011 [13]) with multiple types of safety V2X messages. In this paper we demonstrate the shortcomings of a recently revised version of DCC (v1.2.1, 2018 [6]) and propose 3 modifications, i.e i) Shifting the approach from transmit (Tx) rate control to channel resource control, ii) Setting less severe rate control parameters to maximize channel usage, iii) Adopting continuous and smooth adaptation, instead of abrupt state machine based rate transition. These modifications vastly contribute to ITS-G5 using higher channel capacity, while limiting the channel congestion.

The rest of the paper is organized as follows: Section II presents a brief overview of standardized ETSI DCC, while Section III analyzes the issues and challenges of the Reactive variant of DCC. Section IV presents our proposed improvements, followed by Section V which provides simulation based performance evaluation results. Finally Section VI concludes the paper.

II. ETSI Access DCC - Brief Overview & Analysis

ETSI Access Layer DCC has been specified in the standard ETSI TS 102 687 [6], which describes the TRC mechanism. The input to the TRC algorithm is the Channel Busy Ratio (CBR), calculated as the proportion of time the wireless channel is sensed busy. The output is the Transmit Rate Limit (TRL) or the minimum Inter Transmit Time (ITT) a.k.a *Toff*, an obligatory interval of non-transmission after each transmission, enforced via traffic shaping at the MAC layer. The *Toff* is enforced either using a Reactive mechanism via table lookup or an Adaptive mechanism.

Reactive DCC: Reactive DCC obtains the *Toff* from a lookup table for each range of CBR, as shown in Table I. Each range of CBR corresponds to a DCC state and the variation of the maximum Tx rate w.r.t CBR works as a state machine, as shown in Figure 1. When DCC is in the *relaxed* state, the highest Tx rate is 20 Hz for a CL $< 30\%$, while the lowest rate is 1 Hz for CL $> 65\%$, for the *restrictive* state. The states in between are *Active* states, further divided into states 1, 2 and 3. Transition is only possible between adjacent DCC

TABLE I: Transmit Rate Limit parameters suggested by Reactive DCC of ETSI [6]

State	CBR	Tx rate (Ton 500 µs)	Toff (Ton 500 µs)	Tx rate (Ton 1000 µs)	Toff (Ton 1000 µs)
Relaxed	<30 %	20 Hz	50 ms	10 Hz	100 ms
Active 1	30 % to 39 %	10 Hz	100 ms	5 Hz	200 ms
Active 2	40 % to 49 %	5 Hz	200 ms	2,5 Hz	400 ms
Active 3	50 % to 65 %	4 Hz	250 ms	2 Hz	500 ms
Restrictive	>65 %	1 Hz	1 000 ms	1 Hz	1 000 ms

states, with variation of CBR. Lastly, two TRL are specified for maximum packet airtime *Ton* of up to 500µs and 1000µs, to consider smaller packet size and allow higher Tx rate.

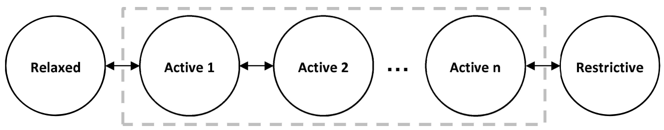


Fig. 1: Reactive DCC State Machine, ETSI TS 102 687 v1.2.1 [6]

Adaptive DCC: The other variant of DCC is Adaptive DCC, which does not involve a table lookup or state machine, but rather limits the duty cycle of each node w.r.t CL, using a variant of the LIMERIC [14] algorithm.

Due to space limitations, Adaptive DCC has not been analyzed in this paper, and the goal of this paper is to improve the performance of standardized Reactive DCC.

III. Analyzing Reactive DCC

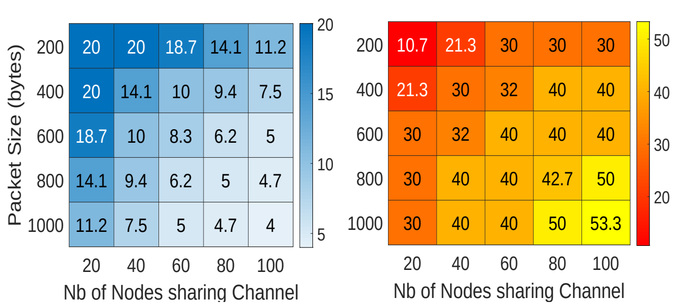
In this section we analyze Reactive DCC and present some design changes in the next section to mitigate its shortcomings.

*1) **Channel Capacity Under-utilization:*** Figure 2a shows the theoretical maximum Tx rate allowed by Reactive DCC, for various combinations of packet sizes (y-axis) and number of nodes sharing the channel (x-axis). Each box indicates the Tx rate allowed to each node, using the TRL of Table I for 500μs *Ton*. We formulate this according to:

$$max_{i \, \epsilon \, n}\left[min\left(\frac{Max\,CL_i * DataRate}{100 * NbNode * PktSize}, Max\,Rate_i\right)\right] \tag{1}$$

In this formulation, for a given pair of packet size and number of nodes sharing the wireless channel, the nodes iterate through each DCC state i, and converge to the state which allows the maximum Tx rate among all the DCC states. Then each node maximizes the Tx rate to reach the maximum CL supported by that state. Fig. 2b shows the CL for the Tx rate in Fig. 2a.

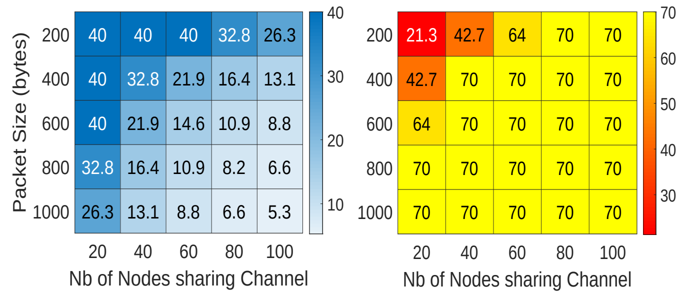
For example, when 40 nodes transmit 400 Bytes packets (Fig. 2a col 2, row 4), the maximum Tx rate is 14.1 Hz, producing a CL of 30%, considering a DataRate of 6 Mbps. It is the maximum rate for this combination, because increasing the rate above 14.1 Hz increases the CL, moving the DCC



(a) Max Tx Rate per Node (b) Channel Load

Fig. 2: Max Tx Rate & CL using Transmit Rate Limit

state to Active 1, with a lower maximum Tx rate of 10 Hz, as shown in Table I. Accordingly, even if 70% channel capacity is unused, Reactive DCC will only allow a maximum TR of 14.1 Hz. This is typically insufficient for nodes having multiple services, such as 10 Hz CAM and 10 Hz Collective Perception Message (CPM) [8].



(a) Max Tx Rate per Node (b) Channel Load

Fig. 3: Max Tx Rate & CL using Channel Resource Limit

Instead of TRL, the temporal channel usage can be controlled using Channel Resource Limit (CRL), i.e. the maximum fraction of time the node is allowed to Tx on the channel, as in Eq. 2.

$$\frac{T_{on}}{T_{on} + T_{off}} = CRL \tag{2}$$

The CRL in fact originates from ETSI DCC management standard TS 103 175 [15], which allows the flexibility or tradeoff between the packet airtime *Ton* and the transmit rate/ITT *Toff*. A node may transmit higher number of smaller packets or few larger ones while respecting the allocated CRL. It does not limit the Tx rate per say, unlike the TRL approach of Reactive DCC.

Figure 3a shows a similar theoretical Tx rate using CRL following Eq. 2, with a channel usage threshold for non-emergency messages set to 70%. This 70% capacity is assumed to be equally shared among the nodes sharing the wireless channel.The highest Tx rate is limited to 40 Hz as set in ETSI EN 302 571 [16]. Reactive DCC via CRL allows a minimum TR of 5.3 Hz and a maximum TR of 40Hz, much higher than TRL. The gain can be explained in Fig. 3b. Reactive DCC via CRL can fully utilize the 70% threshold channel capacity and distribute it among the nodes, without wasting channel capacity unlike Reactive DCC using TRL.

Similarly, the TR differences between the two methods are larger at lower CL than higher CL. Thus Reactive DCC using TRL is inefficient and wastes channel capacity at lower channel loads, while significant channel capacity remains unused.

*2) **Transmit Rate Control ignoring Packet Size:*** In addition to channel under utilization, Reactive DCC via TRL doesn't provide the same granularity in packet size for rate control as CRL. The CRL gives a node the flexibility to adapt its packet size and Tx rate, as shown in Eq. 2. For example, considering a CL $>$ 30%, if each node is allocated 1% of channel resource, it can transmit packets with airtime 1ms followed by an abstention of 99ms, thus transmitting at 10Hz. Similarly, it can transmit 20Hz packets from two applications, with airtime of 0.5ms per packet, still remaining within the allocated CRL.

CBR	Tx Rate	Toff $_{Node}$ ($Ton_{Node} \leq 500\mu s$)
< 30%	20 Hz	50 ms
30-39%	10 Hz	100 ms
40-49%	5 Hz	200 ms
50-65%	4 Hz	250 ms
>65%	1 Hz	1000 ms

Modification 1

$$\frac{Ton}{Ton + Toff} \qquad \frac{500\mu s}{500\mu s + 50ms} = 0.01 = 1\%$$

CBR	CRL
< 30%	1%
30-39%	0.50%
40-49%	0.25%
50-65%	0.20%
>65%	0.05%

Modification 2

CBR	CRL
< 40%	1%
40-49%	0.50%
50-59%	0.25%
60-75%	0.20%
>75%	0.05%

Fig. 4: Converting Transmit Rate Limit to Channel Resource Limit

However, DCC via TRL will keep the state in Active 1 for a CL $>= 30\%$. According to Table I, this will allow 10Hz TR for packet airtime 500µs and 5Hz for airtime 1000µs, instead of 20Hz and 10Hz, as explained above for CRL. This is particularly problematic when a node has multiple services requiring distributing the channel resource among those services with variable packet size.

IV. Improving Reactive DCC

Future/Day 2 applications will be based on multiple Safety services producing packets at heterogeneous rate and size. Accordingly, the limitations of Reactive DCC, identified in Section 3 need to be corrected. We propose three improvements to Reactive DCC and call it as Enhanced Reactive DCC.

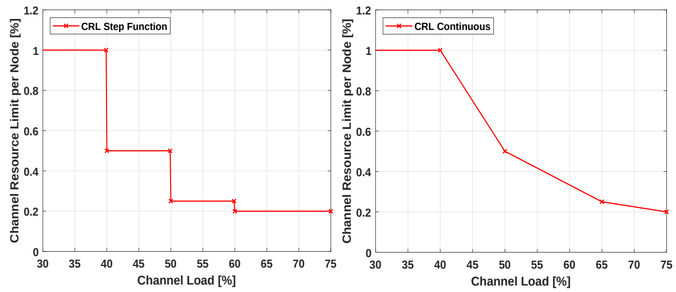
Modification 1: From TRL to CRL
Reactive DCC maps the CL to Tx rate limit without using a continuous relation to the packet size. We transform the TRL of Table I into CRL for each CL interval using Eq 2. For example, transmitting a 500µs (0.5ms) packet at 20Hz (50ms ITT) corresponds to 1% CRL, i.e. 0.5÷50 = 0.01 or 1% CRL, as shown in Fig. 4. This approach can be extended to any lookup table similar to Table I.

Modification 2: Less severe rate control
The TRL in Table I, proposed in the ETSI standard, limits Tx rate from 30% CL. However, as analyzed in the previous section, this creates inefficient channel usage at low CL. Therefore, we propose shifting the CL interval by 10% i.e. starting from 40% CL, as shown in Fig. 4.

A previous study [17] has shown that 70% is the most optimal channel usage threshold, beyond which the packet reception performance decreases due to high collision. Therefore, we propose shifting the CL interval by 10% and not further. This increases the communication performance at lower CL, yet limiting the CL at around 70% as discussed in Section V. In this configuration, the minimum CRL a node can have is 0.05%, while limiting the CL at 75% and accommodating 1500 vehicles in channel, which is sufficient for any extreme road traffic density.

Modification 3: Continuous Relation of CRL w.r.t CL
As discussed in Section II, the Tx rates of Table I are mapped to CL intervals using a state machine resulting a step function. Instead of the step function, we propose a continuous relation of CRL vs CL as represented in Fig. 5. This results a smooth variation of CRL w.r.t CL, instead of rapid jumps. As shown in several previous studies [10], [12], [18], rapid oscillations affect system stability and degrade performance, due to oscillating periods of strong rate restriction followed by sudden relaxation. To further avoid overreaction to rapid CL variation, the new CRL is smoothed as:[1]

[1]A similar filter is applied for CL calculation in the standards [19].



(a) Step Function (b) Continuous

Fig. 5: Modification 3: Step Function to Continuous CRL vs CL

$$CRL(t) = \alpha * CRL(t-1) + \beta * CRL(t) \tag{3}$$

V. Performance Evaluation

In this section, we present simulation based evaluation results comparing the performance of standardized Reactive DCC using the DCC states and parameters of Table I, with our proposed Enhanced Reactive DCC as presented in Section IV.

A 4x4 lane bi-directional 10km sub-urban highway is simulated with vehicles moving between 70 to 90km/h following a Gauss-Markov mobility model, for various levels of vehicle density between 10 to 50 vehicle/lane/km. The maximum vehicle density corresponds to Level of Service (LoS) F of the USA highway capacity manual [20]. Each simulation has been run with a particular vehicle density and average of minimum 30 runs.

Each node is equipped with ITS-G5 transmitters and the ETSI ITS stack. We use the iTETRIS simulator [21], which has a full ETSI ITS protocol stack implemented on top of NS-3. The wireless channel is modeled according to Cheng and Stancil propagation model [22], to correspond to highway channel conditions.

Each node emits 2 safety messages CAM and CPM. The packetsize of CAM is 300 Bytes and are generated using the triggering conditions stated in ETSI EN 302 637-2 [23]. CPM are emitted at a uniform random rate between 1-5 Hz. We simulate CPM of two sizes, i.e. larger CPM of size 650 Bytes and smaller CPM of size 300 Bytes. The values of α and β in Eq. 3 are set to 0.5.

The performance is evaluated in terms of Requested vs Allowed Inter Transmit Time (ITT), Packet Inter Reception Time (IRT), Tx and Rx throughput and channel load. Table II summarizes the main simulation parameters.

Figure 6 shows the average ITT and IRT as milliseconds (y-axis) for various levels of vehicle density between 10 and 50 veh/lane/km (x-axis), using CAM and larger CPM. The average ITT demanded by the vehicles is around 200ms or 5Hz for CAM, and 500ms or 2Hz for CPM for any level of vehicle density (not shown in the graph). However, as the

TABLE II: Simulation Parameters

Parameter	Value
Transmit Rate	CAM triggered, CPM 1-5 [Hz]
Transmit Power	23 dBm
DataRate	6 Mbps
Packet Size	CAM 300 Bytes, CPM 300 & 650 Bytes
Packet Priority	CAM (TC2), CPM (TC 3)
Mobility	Gauss Markov, 4 by 4 lane 10km highway, 10-50 veh/lane/km Speed: 70-90kmh
PHY and MAC	ITS-G5 802.11p in 5.9 GHz (10 MHz Control Channel)
Fading	Cheng and Stancil
Preamble Detection Threshold	- 92 dBm
Performance Indicators	Throughput, ITT, IRT, Channel Load Avg 30 - 50 runs

vehicle density and the CL increase, Reactive DCC increases the ITT to limit the channel load. For the highest density of 50 veh/lane/km, Reactive DCC allows an ITT of 500ms versus the required ITT of 200ms for CAM. Similarly, Fig. 10 shows that Reactive DCC maintains the channel usage at around 45%. Therefore, even if adequate channel capacity being available, Reactive DCC under-utilizes channel capacity, sacrificing performance. Using Enhanced Reactive DCC the CAM ITT remains at around 200ms, even for the highest density. This can be explained using Fig. 10, which shows a channel usage around 70% at the highest density.

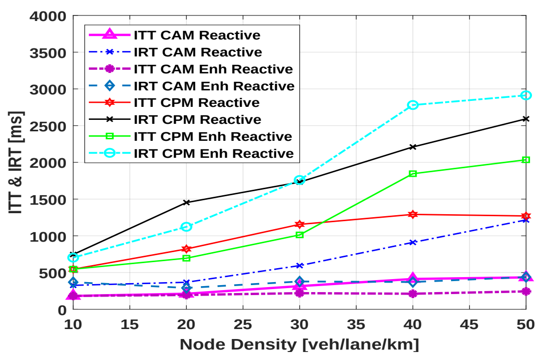


Fig. 6: ITT and IRT (CAM and larger CPM)

Similarly, with Reactive DCC the CAM IRT increases rapidly as the node density or CL increases. This can be explained by Fig. 9, which shows the variation of CL during a 10 second window. When the CL is high, Reactive DCC state machine jumps to a more restrictive state, which limits the Tx rate and decreases the CL. Subsequently, a lower CL doubles or even quadruples the Tx rate (ref Table I), which in fact degrades the communication performance. A rapid jump in Tx rate results a high number of transmissions from neighboring nodes within a short time, increasing the probability of collision, either due to CSMA simultaneous transmission or from hidden nodes. Similarly, Fig. 10 shows a dip in CL of Reactive DCC at the highest vehicle density, which can be attributed to increased packet collision. This issue is mitigated by Enhanced Reactive DCC using CRL instead of TRL and by replacing the rate oscillation with a smooth variation of CRL against CL. Fig. 9 shows the stability of CL using Enhanced Reactive DCC.

With regards to CPM, The ITT and IRT of Enhanced Reactive DCC are better (lower) than Reactive DCC up to a density of 30 veh/lane/km. Afterwards, the ITT of Reactive DCC is better (lower). Although, Enhanced Reactive DCC allocates CRL to each vehicle aiming at maximal channel capacity usage, however inside each vehicle, a higher priority service is fully served before allocating transmission opportunity to lower a priority service. In these simulations, CAM has a higher priority than CPM, so at higher CL, the CRL to each vehicle is insufficient to satisfy both CAM and CPM, so the ITT of CPM is high.

Conversely, Reactive DCC does not maintain a stable channel resource allocation and has oscillating periods of high and low Tx rates, which allows some CPM transmission during transmission peaks. However, the difference between CPM ITT and IRT of Reactive DCC is high due to the same reasoning of Tx rate oscillation and packet collision, as explained earlier for CAM. Therefore, a low CPM ITT does not yield a proportionally low IRT for Reactive DCC, which is problematic considering multiple safety services.

Even if Enhanced Reactive DCC starves CPM at higher densities to ensure better CAM performance, it achieves a better Tx and Rx throughput for both the services combined as shown in Fig. 7. Reactive DCC yields a lower Tx and Rx throughput, which is highly enhanced, almost doubled by Enhanced Reactive DCC.

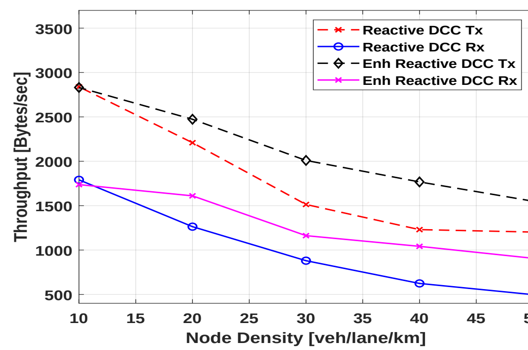


Fig. 7: Throughput (CAM and larger CPM)

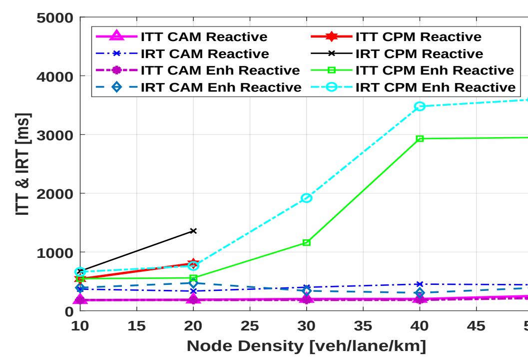


Fig. 8: ITT and IRT (CAM and smaller CPM)

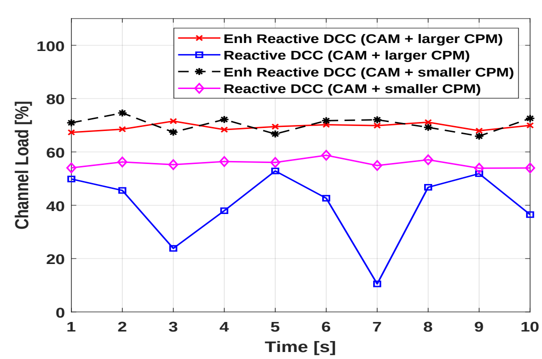


Fig. 9: Channel Load variation in time

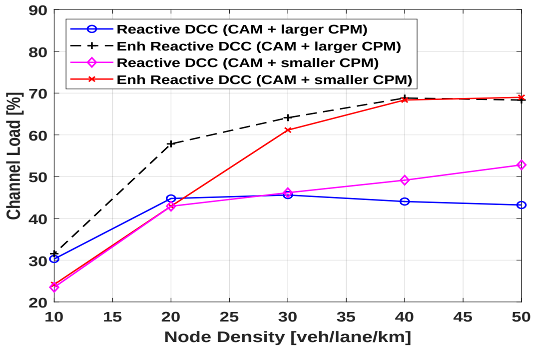


Fig. 10: Channel Load

Figure 8 shows the ITT and IRT when the CPM size is 300 Bytes instead of 650 Bytes as the previous case. The ITT and IRT of CAM are similar for both Reactive and Enhanced Reactive DCC. However, after a density of 20 veh/lane/km, Reactive DCC does not allow any CPM transmission at all, whereas channel usage is merely around 50% as shown in Fig. 10, which also stays stable as shown in Fig. 9, unlike the case with larger CPM.

In these simulations, CPM has lower priority than CAM, so the CPM Tx rate is reduced first during TRC, as the CL increases. In the earlier case, TRC using Reactive DCC and larger CPM causes the CL to fluctuate when the nodes increase or decrease CPM transmission, as shown in Fig 9, due to transmitting or not transmitting a large packet. However, this fluctuation is lesser, when the packet size is smaller, causing the CL to converge and remain stable at 50%. This convergence with smaller CPM size does not allow any peaks of Tx rate, and CPM is completely starved unlike the previous case, which allowed some CPM transmission during oscillation peaks. Enhanced Reactive DCC on the other hand allows CPM transmission even at the highest density, thanks to higher channel usage till 70% as shown in Fig. 10.

VI. Conclusion

In this paper, we evaluated ETSI standardized Reactive DCC, and proposed three improvements to Reactive DCC, which increase the ITS-G5 channel usage and improve the communication performance, while supporting multiple services for future/Day-2 applications under channel congestion.

Firstly, the rate control parameters in the ETSI standard are too severe allowing merely 50% channel usage. We enhanced the channel usage via less severe rate parameters, while still limiting the channel load to 70% even at high vehicle density.

Similarly, Tx rate is not the most optimum unit of limiting temporal channel usage as the CL can fluctuate rapidly with variable and large packet size. This oscillation is further degraded as the variation of Tx rate versus CL follows a step function via a state machine, as proposed in the ETSI standard. Instead of transmit rate control, we demonstrated that channel resource control is much more efficient, which is aided by a continuous relation of the channel resource allocation w.r.t channel load. Overall, our proposed improvements almost double the reception throughput compared to standardized Reactive DCC.

The analysis and improvements in this paper are not limited to ITS-G5 and can be extended to other access technologies. Channel congestion control mechanism for LTE-V2X Mode 4 works similar to ETSI Reactive DCC, mapping the CBR to channel occupancy ratio. Therefore, the improvements we proposed in this paper, can be attempted for LTE-V2X DCC which we intend to investigate in our future work. Similarly, we have not analyzed the other variant of DCC in this paper, i.e. Adaptive DCC, which we will address in our future work.

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