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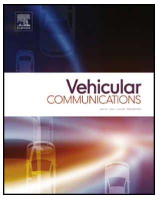

Survey on decentralized congestion control methods for vehicular communication

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ABSTRACT

Vehicular communications have grown in interest over the years and are nowadays recognized as a pillar for the Intelligent Transportation Systems (ITSs) in order to ensure an efficient management of the road traffic and to achieve a reduction in the number of traffic accidents. To support the safety applications, both the ETSI ITS-G5 and IEEE 1609 standard families require each vehicle to deliver periodic awareness messages throughout the neighborhood. As the vehicles density grows, the scenario dynamics may require a high message exchange that can easily lead to a radio channel congestion issue and then to a degradation on safety critical services. ETSI has defined a Decentralized Congestion Control (DCC) mechanism to mitigate the channel congestion acting on the transmission parameters (i.e., message rate, transmit power and data-rate) with performances that vary according to the specific algorithm. In this paper, a review of the DCC standardization activities is proposed as well as an analysis of the existing methods and algorithms for the congestion mitigation. Also, some applied machine learning techniques for DCC are addressed.

1. Introduction

It was 1999 when the U.S. Federal Communication Commission (FCC) reserved 75 MHz of spectrum in the 5.9 GHz band for Dedicated Short-Range Communications (DSRC) in order to support Cooperative ITS applications. Later on, in 2009, the IEEE released the 1609.x family of standards for Wireless Access in Vehicular Environments (WAVE). In 2010 ETSI and CEN formally accepted the European Commission mandate M/453 that invites to prepare the specifications to support the implementation and deployment of C-ITS systems at the European level. This initiative laid the foundations for the standardization of ITS systems at European level taking also into account the harmonization with existing and future standards for C-ITS thanks to the cooperation with organizations and working groups like IEEE, SAE, ISO, IETF and TISA [1]. The first set of standards produced by ETSI under this mandate were released on 2013 and summarized in the Technical Report 101 607 v1.1.1 and updated to v.1.2.1 on 2020 [2]. The specifications for the physical and MAC layers related to the vehicle to everything (V2X) communications were defined by IEEE in the p amendment to the 802.11 family released for the first time in 2007; in 2012 the amendments produced between 2007 and 2011 was included in the new version of the 802.11 standard and the latest one, named IEEE 802.11-2016 [3], was released in 2016 and incorporates the amendments 1 to 5 published in 2012 and 2013. Looking at the frequencies, in Europe only 50 MHz of the 75 MHz of spectrum reserved by the FCC were allocated: the ITS-G5A to road safety related applications (5875-5905 MHz) and the ITS-G5B for ITS non-safety road traffic applications (5855-5875 MHz).

The operation of the C-ITS relies on the exchange of two types of message defined by ETSI as Cooperative Awareness Messages (CAMs) [4] and event-triggered Decentralized Environmental Notification Messages (DENMs) [5]. For the sake of completeness should be mentioned that messages with the same purpose are also defined in the IEEE 1609 family and are standardized by the SAE International as Basic Safety Message 1 and 2 (BSM1/BSM2) [SAE J2735]. The aforementioned Cooperative Awareness Messages are sent periodically in broadcast and carries information like the

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position and the speed of the vehicle, the acceleration, the heading to the north as well as other relevant data of the vehicle (e.g., dimensions, lights status, cruise control). CAMs are essential for the safety as well as for the traffic efficiency applications but, to reach its objectives, C-ITSs also require event triggered messages, i.e. DENMs, to promptly alert the drivers about road hazardous situations. Due to the highly time-critical carried data, it is required that the protocol stack is able to cope with stringent requirements on reliability and latency. Both CAMs and DENMs are broadcasted on the channel dedicated to cooperative road safety, the so called Control Channel (CCH), and this easily leads to the radio congestion in high vehicle-density scenarios. The channel congestion problem was addressed by ETSI and refined in many standards starting from 2011. The proposed approach relies on the Decentralized Congestion Control (DCC) framework that acts on the message rate, the transmit power and the data-rate of periodic messages (i.e., CAMs) to lower the control channel congestion. The newest specifications are released in 2018 within the ETSI TS 102 687 document [6].

In addition to the above IEEE/ETSI standardization activity, recent releases of 3GPP (Third Generation Partnership Project) for the forthcoming 5G provide an alternative (or a complementary) access technology for vehicular communication, i.e. Cellular-V2X (C-V2X). It should be noted that the DCC mechanism designed for the DSRC technologies might not be optimal for C-V2X, as early works suggest [7,8]. However, preliminary DCC solutions have been proposed and defined also for C-V2X, e.g. in [9] and [10]. Further, the hypothesis of a spectrum sharing with the Cellular V2X (C-V2X) technology [11] or the announced reduction of the reserved spectrum by the FCC [12] makes the channel congestion issue even more challenging.

Extensive surveys about congestion control in vehicular networks have been recently published [13–15]. There are also survey papers focusing on more wide range of vehicles, such as UAVs [16–18]. But, to the best of our knowledge, no comprehensive survey focused on ETSI DCC is available yet. In this paper, the ETSI compliant DCC mechanism is addressed with its advantages and limitations. Alternative solutions and approaches are outlined and classified according to different scenarios (e.g., platooning) and control parameters (e.g., transmission rate, transmission power and datarate). The survey has been developed in the frame of cooperations among partners of SafeCop, an ECSEL project mainly focused on cooperative cyber-physical systems and V2X-based services for traffic management scenarios [19]. Within the SafeCop project, a preliminary evaluation of the ETSI DCC has been performed [20] and the channel congestion control issue has been characterized both through simulation [21] and experimental tools [22].

The rest of the paper is organized as follows. The background of some of ETSI standardization activities is described in Section 2, with a focus on ITS-G5 architecture and ETSI DCC specifications. In Section 3, previous ETSI DCC standard performance is evaluated. Section 4 describes the state of the art for papers related to the DCC strategy. We present the existing DCC algorithms and their performance for vehicular communication, meanwhile, pointing out their limitations and challenges. In Section 5 we evaluate applying machine learning for congestion control problems. Finally, Section 6 concludes this paper and points out several paths for future work.

2. Standardization activities

When it comes to safety-critical (and thus time-critical) applications, strict requisites need to be fulfilled transversely. Considerations shall be taken (1) in the lower layer specifications (i.e. access layer), (2) in the specifications of the data traffic to be exchanged (e.g. CAM messages) and also (3) in cross-layer functions such as congestion control mechanisms (e.g. DCC). Accordingly, [23] defines lower layer specifications, while CAM and DENM messages are produced according to [4] and [5] respectively. Last, DCC is defined and communications parameters are adapted according to ETSI TS 102 687 specification [6].

It is important to remark that as specified in [24], even if periodic beacon messages are dispatched via point-to-multipoint communication and ITS access layer includes multiple radio access technologies for the physical and data link layers, DCC strategy is only applicable to ITS-G5. In this section, first ITS-G5 access layer architecture is explained, as specified in ETSI EN 302 665 [23]. Next, ETSI EN 302 637-2 [4] function is presented. Last, ETSI TS 102 687 [6] standard is described in detail.

2.1. ETSI EN 302 665

The ITS-G5 spectrum is comprised of three channels of 10 MHz, from 5.875 to 5.905 GHz to support safety-related applications: one control channel and two service channels. In contrast, IEEE 802.11p proposed a multi-channel operation with seven 10 MHz channels, including CCH, used for safety communications, and six Service Channels (SCHs), used for non-safety applications. As IEEE 802.11a standard [25], ITS-G5 uses Orthogonal Frequency Division Multiplexing (OFDM) modulation scheme. However, the bandwidth used in each channel by IEEE 802.11p is half of what is used in IEEE 802.11a. See Fig. 1.

The MAC layer is based on CSMA/CA and follows the same approach used by IEEE 802.11e EDCA in order to provide QoS support.

2.2. ETSI EN 302 637-2

At first, CAMs were generated every 100 ms and broadcasted to single-hop neighbors. In the latest update [4], the periodic transmission is triggered by using the following rules:

1. the time between two CAMs shall not be lower then $T_{GenCamMin} = 100$ ms and shall not exceed $T_{GenCamMax} = 1000$ ms;
2. a new CAM is generated if one of the following conditions is observed: *(i)* the time passed since the last CAM is larger or equal to $T_{GenCamMax}$; *(ii)* the heading direction exceeds 4° if compared with the heading direction included in the last CAM; *(iii)* the current position has a variation ≥ 4 m if compared with the position included in the last CAM; *(iv)* the current speed exceeds 0.5 m/s if compared with the speed recorded when the last CAM was transmitted.

2.3. ETSI TS 102 687

DCC is a cross layer function and includes components in different layers of architecture, as shown in Fig. 2. In the access layer (DCC_ACC), DCC includes Transmit Power Control (TPC), Transmit Rate Control (TRC) and Transmit Data rate Control (TDC). TPC controls the average transmit power per packet. TRC modifies the duty cycle, i.e. the fraction of time that the node is in *transmit* state. Last, TDC modifies the data rate for transmitting data. Moreover, DCC Sensitivity Control (DSC) adapts the Clear Channel Assessment (CCA) to avoid channel congestion and Transmit Access Control (TAC) uses a transmit queue to handle packet priority.

In April 2018, a new version of the standard ETSI TS 102 687 was presented [6] replacing the previous version (V1.1.1 released in 2011) [26]. In the new standard, two different approaches are described: reactive and adaptive.

The reactive approach includes several DCC-states depending on the current Channel Busy Ratio (CBR) value. CBR indicates the fraction of time the channel is sensed as busy by the considered

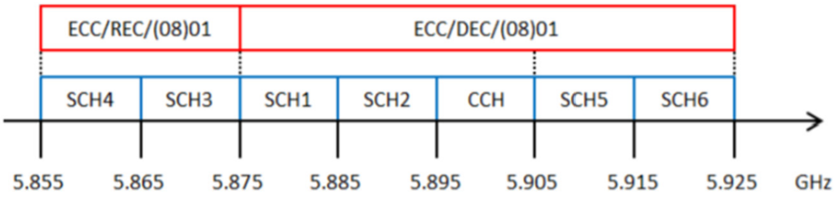

Fig. 1. Overview of frequency band at 5.9 GHz.

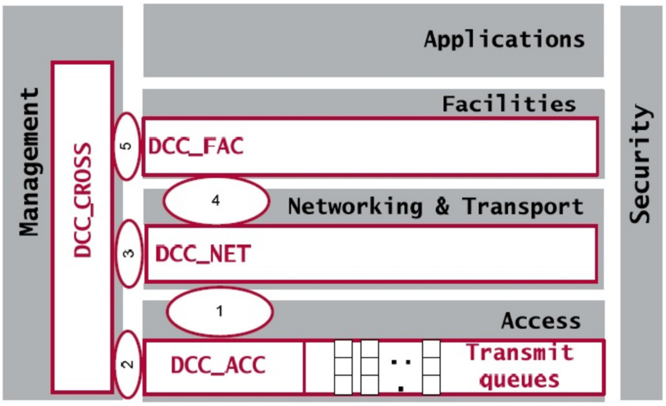

Fig. 2. DCC Architecture [6].

Table 1
Parameter values of adaptive approach.

Parameter	Value	Description
α	0.016	Algorithm parameter.
β	0.0012	Algorithm parameter.
CBR_{target}	0.68	Target CBR.
δ_{max}	0.03	Upper bound on allowed fraction of medium usage.
δ_{min}	0.0006	Lower bound on allowed fraction of medium usage.
G^{+}_{max}	0.0005	Algorithm parameter.
G^{-}_{max}	-0.00025	Algorithm parameter.
T_{CBR}	100 ms	Interval over which CBR is measured. δ is updated at twice this interval.

ITS Station (ITS-S) and is computed every T_{CBR}. Thus, the network load is controlled using the above-mentioned techniques (i.e. TPC, TRC, and so on). An explanatory scheme of the reactive approach is shown in Fig. 3. Restrictive state leads to lower CAM transmission frequencies when the channel congestion is critical, while the relaxed state is enabled when higher CAM transmission frequencies are allowed. However, each state can be reached only from the neighboring states [27].

In the adaptive approach, the DCC algorithm runs in an infinite loop: when Coordinated Universal Time (UTC) modulo 200 ms is zero, the Algorithm 1 is executed.

Algorithm 1: ETSI TS 102 687 adaptive approach.

```
$CBR_{ITS-S} =$
  $0.5 * CBR_{ITS-S} + 0.5 * ((CBR\_L\_0\_Hop + CBR\_L\_0\_Hop\_Previous)/2)$
if $sign(CBR_{target} - CBR_{ITS-S})$ is positive then
    $\delta_{offset} = \min(\beta * (CBR_{target} - CBR_{ITS-S}), G^{+}_{max})$;
else
    $\delta_{offset} = \max(\beta * (CBR_{target} - CBR_{ITS-S}), G^{-}_{max})$;
end
$\delta = (1 - \alpha) * \delta + \delta_{offset}$
if $\delta > \delta_{max}$ then
    $\delta = \delta_{max}$ ;
else if $\delta < \delta_{min}$ then
    $\delta = \delta_{min}$ ;
else
    nothing ;
end
```

CBR_{ITS-S} is the CBR moving average of a given ITS-S; $CBR\_L\_0\_Hop$ and $CBR\_L\_0\_Hop\_Previous$ are the measured local CBR and the second most recent $CBR\_L\_0\_Hop$ respectively. CBR_{target} is the target CBR and the parameter δ is a value that represents the fraction of time ITS-S can transmit. The adaptive Algorithm 1 updates δ to achieve the CBR_{target}. δ_{offset} is the offset value of δ; α, β, G^{+}_{max} and G^{-}_{max} are algorithm parameters to control the algorithm convergence. The basic parameter setting is provided in Table 1.

Further, the adaptive approach implements a gate-keeping function at the MAC layer to satisfy the δ occupancy limit. The gatekeeper state is closed when the access layer cannot accept a packet from the network layer, due to the occupancy limit. The reason to use an adaptive approach is to obtain a steady state CBR that is independent of vehicle density.

3. Evaluation of basic DCC methods

3.1. Drawbacks and performance problems of ETSI DCC

Many papers highlight limitations and performance problems of DCC when the channel load is relatively high. Problems evidenced by many paper are unfairness and oscillations of states [28], [29], [30], [31], [20]. Unfairness consists of different values of messages rate, data rate, etc., for vehicles experiencing the same channel load. In the simplest case, unfairness occurs when two neighbor vehicles must relief channel load but take their decisions at different and uncoordinated times: the first one that switches to a more conservative state, eventually solves the congestion problem for both; since then, both vehicles can confirm their different states, although they operate in the same channel environment. Oscillation occurs when a vehicle switches to a more conservative state to relief congestion, but then switches back to the previous state as the channel is therefore not congested anymore. Upon complex and time varying vehicular scenarios, both mechanisms occur rather quickly and involve multiple vehicles. In particular, in [30], simulation results showed that asynchronous measurements of Channel Load (CL) cause unfairness problems (while synchronous measurements would not provide the real channel occupation). They assumed that each node sends its first CAM at a random time within an interval, and performed a parametric analysis for different widths of such time interval. They observed that DCC is affected by severe instability, influenced by various parameters, including transmit power, queuing time and CCA threshold. DCC also exhibits inefficient usage of channel time. In [27], it throttles the frequency of messages more than needed, penalizing performance of the platooning application. As evidenced in [32], it penalizes collective perception performance, acting as a bottleneck for delivery of Environmental Perception Messages (EPMs). Through the Artery framework, authors simulated V2X communications based on ETSI ITS-G5 with DCC, and examined advertisement of local sensor data among vehicles, to increase awareness of objects in the communication range. As a result, bundling EPMs with CAMs performs better than sending EPMs and CAMs separately. The authors in [33] also highlight problems of DCC when dealing with multiple types of packets, to distribute information about collective perception,

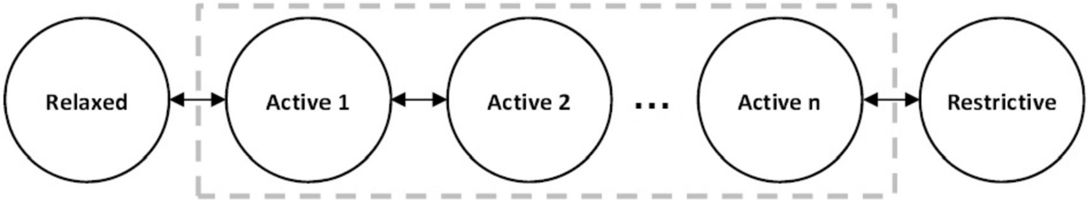

Fig. 3. A generic DCC State Machine of the reactive approach [6].

Table 2
Summary table - Methods of evaluation of DCC.

Ref.	Methodology	Performance Metrics	Tools
[30]	Analysis of unfairness and oscillation problems of DCC.	CBR, CBR oscillation, state divergence between neighboring vehicles. **Variation Factor:** Maximum value of the random time of dispatch of the first CAM.	NS-3, SUMO
[32]	Select the best DCC variant and format of messages to maximize vehicles' awareness.	Awareness ratio, CBR. **Variation Factor:** Data Frame types used for dissemination, DCC state machine variants, V2X market penetration rate.	OMNeT++, Veins, Artery, Vanetza, SUMO.
[34]	Tune DCC parameters to avoid severe connectivity problems that may occur even under non congested vehicular traffic conditions.	Packet Delivery Rate (PDR), received power, CBR. **Variation Factor:** Transmit power, inter-vehicle distance.	Qualnet 4.5 simulator, commercial on-board units (OBUs).

positioning and timing, local dynamic maps. Channel congestion also affects performance of consensus algorithms, that can provide a relevant support for cooperative localization systems, as it is evidenced in [21].

Kuk et al. [34] showed that, even in non-congested conditions, due to the low power setting in restrictive mode, safety messages can not reach beyond immediately adjacent neighbors and the communication range may be even lower than the safety distance between adjacent vehicles, with consequent limitations to delivery of safety-related information. The authors evaluated ETSI DCC using simulations and real world experiments. Results evidence unsuitability of standard values of transmit power and receiver sensitivity in restrictive mode. Higher transmit power raises the channel utilization to an adequate operating range, thereby solving connectivity problems. However, more effective methods should be found in the future.

3.2. *Proposals to improve ETSI DCC performance*

Main techniques proposed to cope with conventional ETSI DCC drawbacks fall into the following approaches:

- Account for channel perception and/or status of neighboring vehicles [28], [29];
- Using multiple Active sub-states [31];
- Tuning one or more parameters in DCC states: message delivery rate (TRC), bit rate (TDC), transmission power (TPC), channel load and clear channel assessment thresholds, and so on [35], [36], [37], [38], [20], [39].

Multiple techniques can also be combined, as in [40].

Some papers also focus on multiple DCC mechanisms in different layers [33] and on the option of a cross-layer approach [35].

The following subsections survey literature works based on the above mentioned approaches, whereas Table 2 summarizes main outcomes of papers that provide different contributions.

3.2.1. *Sharing channel and/or DCC status*

In papers [28] and [29], authors suggest that knowledge of status of neighbors may help DCC to mitigate fairness and oscillation issues.

Kuk and Kim [28] focused on frequency of delivery of beacon messages and measured fairness through the Jain index. They observed that the DCC mechanism can lead nearby vehicles to select different states and then consolidate and reinforce this divergence. Therefore, they proposed an amended version of DCC: adding a check against the neighbors' average state before committing a change, the unfairness problem can be effectively mitigated.

In [29], Autolitano et al. investigated different CBR measurement methods for DCC under different traffic densities, to get better understanding of channel load. They analyzed the correlation between CBR as locally measured by the generic vehicle, denoted as CBR_0, and as the maximum measured and reported by one–hop and two–hops neighbors, i.e. CBR_1 and CBR_2, respectively. Extensive simulation experiments have been conducted for an urban scenario, to observe the influence of obstructions on CBR measurements. Results highlighted that CBR_0 is markedly dependent on the number of neighbors within the communication range. CBR_2 is basically equal to CBR_1, that hence allows all nodes to account for the effects of hidden terminals and be aware of the maximum CBR in their radio range. See Table 3.

3.2.2. *Using multiple active sub-states*

In [27], DCC is named as DCC+1 and compared with DCC+3 and DCC+5 variants as specified by ETSI, where DCC+N employs N Active sub-states. TRC is considered for a platoon consisting of 15 vehicles, disturbed by a slower vehicle approaching from a highway ramp. Considered performance metrics are: variation of inter-vehicle gaps, CBR, age of CAMs that the leading vehicle receives from the last vehicle. DCC+1 entails lower CBR values: upon dynamic changes that trigger a larger number of CAMs, the basic DCC algorithm directly switches from the Relaxed to the unique Active state, without any intermediate CAM frequency option between 10 and 2 Hz. Alas, this may drastically reduce the CBR

Table 3
Summary table - Improving DCC performance, sharing channel and/or DCC status.

Ref.	Methodology	Performance Metrics	Tools
[28]	Improve fairness for the same CBR.	Fairness measured through a Jain index over the number of messages delivered by vehicles per second. **Variation Factor:** Vehicular traffic density.	Qualnet 4.5
[29]	Provide a criterion to let the vehicles estimate the maximum CBR in the radio range.	CBR_0, CBR_1, CBR_2, maximum CBR. **Variation Factor:** Number of vehicles, CCA threshold.	NS-2, SUMO

Table 4
Summary table - Improving DCC performance, using multiple active sub-states.

Ref.	Methodology	Performance Metrics	Tools
[27]	Avoid penalization of C-ITS application performance when preventing channel congestion.	Variation of inter-vehicle gaps in the platoon, CBR, age of CAMs. **Variation Factor:** Number of Active sub-states.	PLEXE: OMNeT++, Veins, SUMO.
[31]	Improvements of performance metrics through a more granular TDC.	Number of messages delivered to neighbors, average CBR, CBR oscillation, CBR unfairness. **Variation Factor:** Density of vehicles.	Qualnet 4.5
[40]	An appropriately tuned DCC with multiple Active sub-states is suitable to cope with variable density of vehicles, providing dependability for safety related messages.	CDF of the MAC-to-MAC delay, CCDF of coverage ranges, data novelty. **Variation Factor:** Carrier Sensing Threshold (CST) parameterization, number of Active sub-states.	Matlab

markedly below a safe threshold, at the expense of a larger age of CAMs and hence of information available within the platoon. The DCC+3 and DCC+5 variants perform better, as they offer a more granular choice of the CAMs frequency and do not throttle it exceedingly. They prevent the channel congestion with a better age performance metric, with relevant benefits for dynamic situations that require a timely information delivery. Authors identify a DCC weakness in the mechanism basically intended only at preventing network failure for channel congestion, without optimizing performance of overlying C-ITS applications. Hence they point out the importance of identifying the effect, on C-ITS applications performance, of limitations enforced on the CBR.

Yang and Kim [31] evidenced that instability and unfairness are brought by marked differences between DCC parameters in different states. They proposed an amendment based on TDC and named as Simple DCC (SDCC): to reduce the gaps between states, two more states are added. SDCC performance are compared to LIMERIC [41], as both methods adjust CBR. The results show that SDCC acts on the duration of messages (via TDC), whereas LIMERIC continuously adapts their rate. The authors provide similar performance and SDCC effectively copes with stability and fairness issues of ETSI DCC. For medium to high densities of vehicles, the number of delivered messages is larger for SDCC at the most safety-critical distances, and for LIMERIC at larger distances.

Alonso Gómez and Mecklenbräuker [40] evaluated the performance of the plain EDCA protocol, the standard DCC, and an alternative DCC design with more Active sub-states, implementing TPC, TRC, and Carrier Sensing Threshold (CST) parameterization. A dynamic traffic highway scenario is considered, consisting of two vehicle groups approaching, merging and then separating; system dependability is evaluated, as a key point for safety-related communications. Upon such fast variations of the vehicles density, transient drawbacks can be eased if vehicles share information on the perceived channel state. Results showed that system dependability is provided by the proposed DCC version with multiple Active sub-states. See Table 4.

3.2.3. *Tuning DCC parameters*

Le et al. [36] compared through NS-2 simulations the performance of TPC, TRC, and TPC combined with TRC, without implementing DCC, w.r.t. channel busy time (CBT) and the ability to reserve bandwidth for event-driven warning messages. The results showed that all the three methods improve performance over the baseline results with no congestion control. They are suitable for different situations, and TPC combined with TRC is the most flexible one among them. This confirms effectiveness of these basic algorithms included in DCC.

Vesco et al. [38] evaluated DCC performance through extensive simulations using NS-2 simulator for two scenarios: Line-Of-Sight (LOS) and urban. The authors studied the impact of different DCC mechanisms as well as their combinations on the system performance. The results highlight that DCC has little effect. Moreover, the DCC behavior is mainly determined by the TRC mechanism, which may even decrease the overall performance compare to the legacy 802.11p MAC protocol.

Autolitano et al. [37] assessed DCC behavior and performance through NS–2 simulations. Single DCC mechanisms, such as TPC, TRC, and DSC, are implemented and compared separately, in order to get insights on the impact of each adaptation mechanism on the overall DCC performance. Also, a DCC scheme where TPC, TRC, and DSC are simultaneously active is evaluated. All these schemes are compared against the legacy solution, where the 802.11p MAC layer is not provided with congestion control mechanisms. The results highlight that TRC outperforms other mechanisms; TRC and TPC are the most effective ones. As a general remark, as A. Vesco et al. in [38], they observed that DCC is not effective with currently specified parameters settings. They also showed that the high rate of transmissions in legacy DCC means that more than half of transmissions would collide with others, which is unacceptable for safety applications. It can be evidenced that, in the final considerations, [37] states that timing and CL threshold parameters should be carefully set to reduce states transitions. The

Table 5
Summary table - Improving DCC performance, tuning DCC parameters.

Ref.	Methodology	Performance Metrics	Tools
[20]	Mitigate unfairness and CBR/DCC state oscillations, through adaptive settings of parameters of the DCC state machine.	CBR, state oscillation, transmitted messages/second. **Variation Factor:** Parameters of the DCC state machine: CL_{min}, T_{down}.	Cohda Wireless MK5
[36]	Investigate effectiveness and flexibility of power and/or rate control in mitigating congestion and improving the reception rate of event-driven warning messages.	Reception rates of beacon and warning messages vs distance between sender and receiver, Channel Busy Time (CBT) ratio vs distance to intersection center. **Variation Factor:** Number of lanes of the intersection, density of vehicles, mean inter-vehicle distance.	NS-2
[37]	Assess effectiveness and main features of principal DCC mechanisms.	Packet Delivery Ratio (PDR), update delay of CAMs, average Channel Load (CL), statistics of DCC states and their transitions. **Variation Factor:** Distance between transmitter and receiver, packet size, density of vehicles.	NS-2
[38]	Investigate the impact of DCC mechanisms on system performance. DCC behavior turns out to be determined mainly by TRC.	Packet Delivery Ratio (PDR) vs receiver distance, packet access delay, distribution of DCC states vs distance from the nearest intersection. **Variation Factor:** Signal attenuation model, data packet size.	NS-2
[39]	All considered variations of ETSI ITS-G5 provide effective congestion control, contrarily to IEEE WAVE.	Rate of generated, delivered, and lost beacon messages, channel load. **Variation Factor:** Vehicular scenario: speed range, kind of trajectories, density of vehicles, beacon size.	OMNeT++, Veins, SUMO.

experimental work by Cinque et al. [20] confirms that tuning this kind of parameters is a key point to improve stability of DCC.

Cinque et al. [20] experimentally showed that unfairness problems, as well as fluctuations of CBR and states, can be solved if ETSI DCC parameters defined in [6] are properly set, i.e., adaptively reducing the CL_{min} channel load threshold and increasing the T_{down} reaction time. However, the work remarks that a too low CL_{min} can decrease the throughput excessively. It is also pointed out that a cooperative implementation of this adaptive strategy is a key point for effective optimization of the DCC behavior.

In [39], the authors compared the ETSI ITS-G5 and IEEE WAVE standards through the Veins simulator, for three different single-hop scenarios: motorway junction, urban, and traffic jam. Standard values of the DCC operating parameters are considered, along with two variations to shorten the packet intervals and to determine them dynamically, based on the LIMERIC algorithm. IEEE WAVE does not provide effective methods to relieve the channel load, hence similar congestion conditions occur for all scenarios; on the contrary, all variations of ETSI ITS-G5 successfully keep the channel load within about 10%. See Table 5.

3.2.4. Multiple DCC mechanisms and cross-layer approach

Schmidt et al. [35] proposed a cross-layer framework which can involve different DCC mechanisms, including TDC, TPC, and TRC. The paper introduced requirements for DCC layers in detail: Management, Facilities, Network, and Access, as shown in Fig. 2. Parameters to be optimized involve multiple strategies located at different layers, therefore the authors suggest that a cross-layer approach is needed to choose the best trade-offs dynamically, according to load and communication purposes. Shortly, a single mechanism can be even counterproductive, as proved by related works, whereas it can be useful if it works in combination with others.

The work in [33] highlights the problems of DCC Access when dealing with multiple types of packets:

- Collective Perception Message (CPM), to share various sensor information with other ITS stations;
- Position and Time Message (POTI), to obtain precise position and time from other ITS-Ss;
- Local Dynamic Map (LDM) messages, to exchange LDM information [42].

TRC can bound the number of emitted packets, either via queuing and flow control, or by limiting packets generated by V2X services. DCC Access adopts the former technique, whereas DCC Facilities resorts to the latter one. When dealing with multiple services, DCC Facilities alone achieves higher packet reception rate, due to the absence of transmission bursts (caused by queuing), whereas DCC Access may hinder DCC Facilities operation. Hence, authors suggest to handle congestion control and channel resource allocation through DCC Facilities and DCC Management, without DCC functionalities in the Access layer. As a drawback with DCC Facilities, lower priority packets may be blocked during resource constraints. See Table 6.

4. State of the art of DCC

During the last decade, many decentralized congestion control techniques have been proposed from the research community to enhance the performance of ETSI DCC standard. However, to the best of our knowledge, there is no comprehensive survey paper in this field, or at least no recent survey that would cover the new papers. There is only one paper by Song and Lee [13] published in 2013 that collects different DCC methods, considering different performance metrics, such as Beacon Reception Rate (BRR), Emergency message Reception Rate (ERR) and CBR. Here, numer-

Table 6
Summary table - Improving DCC performance, using multiple DCC mechanisms and cross-layer approach.

Ref.	Methodology	Performance Metrics	Tools
[33]	Full exploitation of the allowed channel load may block low-priority traffic, due to mechanisms of DCC in multiple layers.	Transmission and reception rate of different kinds of messages, CBR. **Variation Factor:** Enabling Facility-layer DCC either with or without Access-layer DCC.	NS-3, ITETRIS.
[35]	Cross-layer management of the DCC, to optimize its efficiency and effectiveness.	Network capacity, efficiency of channel usage. **Variation Factor:** Parameters of all principal DCC mechanisms, priorities of different types of messages.	–

ical results prove that the IEEE 802.11p MAC protocol does not perform well under high channel load in both highway and urban scenarios. A more general survey on adaptive beaconing approaches for vehicular environment is instead presented in [43]. In this work, Ali Shah et al. considered both American WAVE and European ETSI standards, and assesses the potential of beaconing techniques through different key performance indicators. Considered indicators included: channel load, congestion control scheme, fairness, reliability, data utility distribution and co-existing message dissemination. However, [43] does not specifically deal with DCC performance evaluation.

In this section, several papers related to DCC-based techniques are classified and discussed with the aim to derive open challenges and future research directions. We divided the existing papers by considering three main kinds of control techniques: 1) Transmit Rate Control (TRC), 2) Transmit Data-rate Control (TDC) and 3) Transmit Power Control (TPC). Hybrid and further control techniques are also discussed in subsection 4.4 and 4.5, respectively. [43], [44] and [45] use a similar categorization, where [44] and [45] compare and validate several beaconing approaches for generic vehicular ad-hoc networks. Described papers are summarized in Tables 7–15 at the end of each paragraph.

4.1. Transmit rate control (TRC)

In this section the most cited TRC approaches are outlined by taking into account also their possible developments.

4.1.1. TRC for platooning scenarios

Zheyuan in his work [46] examined the performance of ETSI DCC under a platooning scenario. He implemented a TRC technique for DCC using PLEXE simulator under highway scenarios. The results show that when beacons are generated with a static frequency (in this work, 10 Hz and 20 Hz) the platoon performance is better than by using CAM-generation kinematic rules defined in [4]. Specifically, when the CAM-generation rate is static, vehicles move more coordinately and synchronously.

A study of platooning performance under ETSI ITS-G5 is also provided in [47]. Specifically, Lyamin et al. implemented the ITS-G5 stack with DCC and measured the fuel consumption of platooning application also using PLEXE simulator. Simulation results proved that TRC with multiple ACTIVE sub-states reduces fuel consumption.

4.1.2. LIMERIC and its variations

LIMERIC [41] is a distributed and adaptive linear control algorithm and is today one of the most cited approach. In LIMERIC each vehicle j adapts the message transmission rate R_j with the aim to make the CBR to converge to a given target value. Then, the transmission rate can be updated from time $t-1$ to time t according to the linear adaptive formula (1).

$$R_j(t) = (1-\alpha) * R_j(t-1) + \beta * (CBR_T - CBR(t-1)) \qquad (1)$$

$CBR(t-1)$ and CBR_T are the measured CBR at time $t-1$ and the target channel load, respectively. α and β are convergence factors influencing the convergence and stability of states. In [48], the same authors compared the performance of ETSI DCC with LIMERIC in terms of Inter Packet Gap (IPG) and Tracking Error (TE), by using the NS-2 simulator. IPG indicates the time between two consecutive received packets, showing the reliability of the received information. TE measures the error between the transmitter's real location and the receiver's measurement. The results prove that LIMERIC achieves lower IPG and TE than the ETSI DCC.

Bansal et al. extended in [49] the LIMERIC algorithm to adapt the message transmission to the vehicle's action. They introduced an Error Model Based Adaptive Rate Control (EMBARC), in which vehicles with higher dynamics have more transmission opportunities. Through simulation experiments using SUMO and NS-2, Bansal et al. proved that EMBARC not only has the advantage of LIMERIC (i.e., a good throughput even with a high number of neighbors), but also is able to obtain a massive packets transmission using an intelligent future-looking TE estimate.

In [50], Cheng et al. analyzed the performance of ETSI DCC and LIMERIC in a heterogeneous scenario, where some vehicles exploit ETSI DCC, while others vehicles implement the LIMERIC algorithm. The results show that the ETSI-DCC vehicles could potentially experience a performance degradation after introducing the LIMERIC vehicles into the network, in terms of both Packet Error Rate (PER) and IPG. In [51], the same group of authors found a solution to solve the ETSI-DCC performance degradation issue. They proposed a Channel Busy Percentage (CBP) target adjustment for LIMERIC based on vehicle densities. Simulation results demonstrate that the ETSI-DCC vehicles perform better when the LIMERIC target adjustment is used. Moreover, the LIMERIC vehicles maintain similar or better performance.

4.1.3. The unfairness issue

As highlighted in Section 3, there have been several papers focusing on fairness for congestion control techniques. In this perspective, in [52], Tielert et al. proposed PULSAR (Periodically Updated Load Sensitive Adaptive Rate control), a TRC technique. In PULSAR, each ITS-S triggers the transmission rate adaptation by comparing each CBR measurement with a CBR target value. Also, a 2-hop piggybacking mechanism is introduced to make all nodes within the Carrier Sense (CS) range able to participate in congestion control. The CS is the minimum distance from a transmitting radio in which the receiving radio can distinguish the received signal from the noise. Simulation results show that PULSAR is suitable for real-time safety applications and that the 2-hop piggybacking mechanism can effectively mitigate local and global DCC unfairness problems.

With the same objective to mitigate the unfairness problem, in [53], Bansal and Kenney proposed an extension of the LIMERIC algorithm. The authors modified the LIMERIC algorithm to converge

Table 7
Summary table - TRC for platooning.

Ref.	Methodology	Performance Metrics	Tools
[46]	Static CAM-generation rate is compared with kinematic generation rules. It is shown that: *(i)* static rate performs better in platooning scenarios; *(ii)* DCC with several ACTIVE sub-states has advantages	Channel Load, n. of transmitted messages, speed synchronization **Variation Factor:** Tx rate, number of ACTIVE sub-states	PLEXE
[47]	Performance of DCC with multiple ACTIVE sub-states is evaluated in platooning scenarios	Fuel efficiency, speed fluctuation **Variation Factor:** number of ACTIVE sub-states, Tx-Rx distance	PLEXE

Table 8
Summary table - LIMERIC approach for TRC.

Ref.	Methodology	Performance Metrics	Tools
[41]	LIMERIC implementation to achieve fair and efficient channel utilization	CBR, speed of convergence to CBR_{target} **Variation Factor:** vehicle density	NS-2, Matlab
[48]	LIMERIC is compared to ETSI DCC and achieves better performance w.r.t lower packet gap (IPG) and tracking errors	CBR, PER, IPG, TE **Variation Factor:** vehicle density	NS-2
[49]	LIMERIC is extended to preemptively schedule messages based on the vehicle's movement	PER, IPG, TE **Variation Factor:** vehicle density	NS-2, SUMO
[50]	This work considers the situation where ETSI DCC and LIMERIC co-exist	PER, IPG **Variation Factor:** DCC Tx rate, LIMERIC CBR_{target}, vehicle density	NS-2, SUMO
[51]	ETSI-DCC performance is observed and it is shown that it improves when ETSI-DCC and LIMERIC co-exist	PER, IPG **Variation Factor:** DCC Tx rate, LIMERIC CBR_{target}, vehicle density	NS-2, Matlab

to weighted fair message rates, e.g. to have an equal transmission rate among ITS-Ss in a given area. As the traditional LIMERIC method, also the proposed algorithm controls the total channel load according to a target, but in this case each vehicle converges to a message rate proportional to its weight. By referring to the LIMERIC equation (1) the technique uses the adaptation parameter β with the aim to achieve fair transmission rate allocation among vehicles. In the modified-LIMERIC, each node j is assigned a different parameter β_j, which is associated with a desired weight w_j. The algorithm will converge such that the ratio among the steady state message rates of the nodes is the same as the ratio of β parameters. The simulation, based on NS-2 simulator, showed improvements regarding fairness.

Also in [54], Lorenzen and Garrosi proposed a LIMERIC variation. The authors mentioned that in LIMERIC, fairness decreases due to the hidden terminal problem. Therefore, they proposed a cooperative LIMERIC (C-LIMERIC) and compared it with PULSAR. The simulation experiments showed that C-LIMERIC converges to a stable state faster than PULSAR. However, PULSAR performs better in terms of Probability of Packet Reception (PPR) when the vehicles density increases. Also, the authors did not show the benefits of C-LIMERIC to the regular LIMERIC algorithm.

In [55], Kim et al. proved that both LIMERIC and PULSAR are lack of fairness. By referring to the American WAVE standard, the authors proposed a remedy to the unfairness pathology, which is composed of two steps. First, each vehicle shares its current rate assignment in the WAVE Basic Safety Message (BSM). Second, using the averaged rate as a safeguard, they only change their rates if it does not violate the safeguard. This coordinative approach leads to a stable control so that vehicles in the same neighborhood converge to the same rate. The effect of the proposed solution is demonstrated through simulation experiments.

The same issue is addressed in [56]. In this work the transmission rate allocation problem is modeled as a Network Utility Maximization (NUM) problem. Specifically, the authors apply the NUM theory to design a set of decentralized control algorithm, e.g. FABRIC (Fair Adaptive Beaconing Rate for Inter-vehicular Communications). FABRIC is compared with LIMERIC and PULSAR and numerical results show that the proposed algorithm mitigates unfairness problems.

4.1.4. The scalability issue

Another important factor to design a channel congestion control method is scalability, which means that the method has to offer the same stability in both dense and light conditions. In [57], Lorenzen proved that the LIMERIC algorithm is not stable under high vehicle density scenarios due to fixed convergence parameters. In fact, in the LIMERIC equation (1), the parameter β needs to be either parametrized to guarantee stability under high vehicle densities or needs to be dynamic. In this regard, the authors of LIMERIC propose a slowly reacting second loop to control β [41], while in [57] Lorenzen proposed a fast reacting Self-Weighted Rate Control (SWeRC) algorithm by adding a dynamic in-time weighting of β based on the group-rate. Numerical results show that SWeRC achieves better scalability and fairness compared to LIMERIC.

The scalability issue is also addressed in [58], where Rostami et al. compared ETSI DCC with LIMERIC in terms of stability. As mentioned in previous sections, ETSI DCC is a reactive state-based algorithm, which means that the state changes according to the measured CBP. To improve ETSI DCC performance, the author proposed a stable reactive algorithm, where asynchronous CBP measure-

Table 9
Summary table - TRC: the unfairness issue.

Ref.	Methodology	Performance Metrics	Tools
[52]	PULSAR algorithm to achieve local and global fairness	Tx rate, CBR **Variation Factor:** Tx-Rx distance, node position, static and dynamic scenarios, PULSAR configuration	NS-2
[53]	Variation of the LIMERIC algorithm to mitigate the unfairness problem	CBR, Tx rate, PER, IPG **Variation Factor:** LIMERIC β parameter, vehicle density	NS-2
[54]	Cooperative LIMERIC to cope with the hidden node issue	CBR, Tx rate, PPR, IPG **Variation Factor:** vehicle density, node position	OMNeT++
[55]	A remedy to the unfairness pathology by referring to the WAVE standard	CBR, Tx rate **Variation Factor:** threshold-based and hysteresis-based control algorithms	Qualnet 4.5
[56]	NUM theory applied to DCC to achieve fairness	CBT, IRT, Tx rate **Variation Factor:** propagation model, path loss exponent, LIMERIC α parameter, vehicle density, vehicle position	OMNeT++

Table 10
Summary table - TRC: the scalability issue.

Ref.	Methodology	Performance Metrics	Tools
[57]	LIMERIC stability is analyzed under high vehicle densities	CBR, Tx rate, speed of convergence **Variation Factor:** LIMERIC convergence parameters, vehicle density	OMNeT++
[58]	ETSI DCC is compared to LIMERIC in terms of stability	CBP, PER, IPG, TE, Tx rate **Variation Factor:** Tx-Rx distance, vehicle density	NS-2, SUMO

ments and continuous message rate adaption are performed. Still, comparing this algorithm to LIMERIC, the latter always achieves lower IPG and TE. This result is due to the LIMERIC's capability to achieve a given CL target, independent of vehicle density.

4.1.5. *Adapting to physical topology and vehicles' dynamics*

Another topic of interest concerns the use of TRC methods for rear-end collision avoidance. Lyu et al. [45] investigated a rear-end collision model and defined a danger coefficient ρ to characterize the collision-risk of each vehicle. ρ is a function of the speed and distance to neighbors, which becomes very large when the speed is fast and the distance gets small. In the proposed model, those vehicles with a small value of ρ can reduce beacon rates to save the channel resource. On the contrary, vehicles with a high value of ρ should increase the beacon rate to avoid the potential dangers. Moreover, when a vehicle identifies a channel congestion event, it adopts a greedy algorithm to locally solve a Distributed Beacon Rate Adapting (DBRA) problem. In the presented DBRA problem, all vehicles are first assigned with the minimum beacon rate α_{min}; for the remaining medium resource, vehicles are ranked according to the danger coefficient ρ. The vehicle with the largest ρ receives more medium resource until reaching a maximum value α_{max}; this procedure repeats until the whole medium resource is used.

Lyu et al. found that non-line-of-sight (NLoS) conditions are the key factors of Packet Delivery Ratio (PDR) degradation within the vehicular environment. In [59], they proposed a Distributed Beacon Congestion Control (DBCC) scheme with link perception, by using two different machine learning methods to conduct NLoS link condition prediction. Thus, they have formulated the Link-weighted Safety Benefit Maximization (L-SBM) problem to adapt the transmission rate when TDMA MAC is exploited. A greed-based heuristic algorithm is then proposed to solve the problem. The performance of the algorithm are evaluated through Matlab/SUMO simulations and the proposed DBCC solution is compared with both conventional 802.11p and PULSAR. Further details will be shown below, in Section 5. The resilience of the DCC mechanisms in a mobile NLOS situation is also tested in the ETSI Technical Report [60].

A further TRC technique is proposed by Barbieri et al. in [61]. By referring to the ETSI ITS standard, they proposed a Beaconing Adaptation for Safety Enhancement (BASE) which adapts the Beacon Periodicity (BP) to minimize the channel resources while taking care of safety requirements. The principle of BASE is that each vehicle chooses the BP based on the maximum BP of the preceding and following vehicles. Analytical results showed that BASE can significantly reduce channel congestion and satisfying challenging requirements for safety.

4.2. *Transmit data-rate control (TDC)*

Since LIMERIC decreases the message-rate to reduce congestion without increasing the channel capacity, authors in [62] proposed a Data-rate DCC technique (DR-DCC) as an improvement for LIMERIC. DR-DCC increases the data-rate to reduce congestion, effectively making messages shorter in time and increasing channel capacity. Like LIMERIC, DR-DCC maintains a higher message-rate even at high traffic densities. Moreover, it increases the channel capacity and achieves better application reliability. This adaptability makes it suitable for different kinds of traffic scenarios. Simulation results show that DR-DCC performs better than a TPC algorithm in terms of average Inter-Reception Time (IRT). However, the comparison between DR-DCC and other TRC or TDR mechanisms is missing here.

Like the TRC techniques, also DR-DCC can easily result in unfairness. In DR-DCC data rate values are selected by considering only

Table 11
Summary table - TRC: Adaptive techniques.

Ref.	Methodology	Performance Metrics	Tools
[45]	TRC methods for rear-end collision avoidance	Tx rate, efficiency ratio of transmissions, rate of beacon receptions, rate of reception collisions **Variation Factor:** Danger coefficient, DCC technique.	SUMO, Python
[59]	A Distributed Beacon Congestion Control (DBCC) scheme with NLoS link condition prediction	PDR, safety benefit, algorithm running time, rate of beacon receptions, rate of reception collisions, Tx rate, efficiency ratio transmission **Variation Factor:** Road environment, LoS conditions, L-SBM algorithm, DCC technique.	SUMO, Matlab
[61]	Beacon Periodicity (BP) is adapted to minimize the channel resources while taking care of safety requirements	Tx rate **Variation Factor:** Speed, reaction times, positioning error.	-

Table 12
Summary table - Transmit Data-rate Control.

Ref.	Methodology	Performance Metrics	Tools
[62]	A Data-rate DCC technique to maintain a higher message-rate even at high traffic densities	CBR, IRT **Variation Factor:** DCC technique, vehicle density, Tx-Rx distance.	NS-3, SUMO
[63]	A novel Packet-count DCC algorithm to achieve better fairness if compared to LIMERIC and DR-DCC	CBR, Jain's fairness index, T-window reliability **Variation Factor:** Tx data rate, vehicle density, Tx-Rx distance.	NS-3, SUMO

the measured CBR, so vehicles with similar CL conditions can obtain different data rate setting. To cope with the unfairness issue, a novel Packet-count DCC algorithm (PDR-DCC) is presented in [63]. The proposed method uses Packet Count (PC) together with CBR measurements, where PC indicates the number of packets sensed by a vehicle in a given period. With this approach, vehicles experiencing similar channel loads have a similar packet count and thus the same data-rate. The authors used simulation experiments to compare LIMERIC and DR-DCC. Numerical results showed that PDR-DCC outperforms both DR-DCC and LIMERIC in terms of fairness and reliability.

4.3. Transmit power control (TPC)

Safety-oriented applications require massive dissemination of beacons. Therefore, TRC mechanisms may not meet the necessary requirements in safety scenarios. Torrent-Moreno et al. [64] proposed a Distributed Fair Power Adjustment for Vehicular environments (D-FPAV) method based on TPC to ensure messages with higher priority receive sufficient bandwidth. Simulation results show that D-FPAV ensures a high Packet Reception Rate (PRR) while preserving low values of channel load. Moreover, the authors proposed an Emergency Message Dissemination for Vehicular environments (EMDV) for the multi-hop dissemination of DENMs. The following factors have an important impact on increasing the reliability of the EMDV process: *(i)* a shorter forwarding range and *(ii)* an adaptive re-transmission scheme. Simulation results show that EMDV can benefit from D-FPAV in terms of PRR and latency.

TPC design is usually complex, since it involves highly dynamic networks. However, it is particularly suitable for simplified and linear network topologies, such as in platooning scenarios. Segata et al. in [65] investigated different communication strategies for platooning, exploiting synchronized communication slots integrated with TPC techniques. The proposed method is then compared with other beaconing solutions, e.g. static beaconing and conventional ETCI DCC for automated platooning applications. Simulation results show that the proposed approach can effectively mitigate collisions. Further, they considered a mixed scenario in which some vehicles concurrently access channel using ETSI DCC. It is shows that the performance of the proposed solution is unaltered, while ETSI DCC performances are heavily affected.

Jimenez [66] in his work proposed two DCC new methods. The first one is TPC with a Proportional Integral (PI) control loop (TPC PI). The second is TPC with a PI control loop coupled with the exchange of Channel Load Share information (TPC CLS). In comparison to ETSI DCC, both of these methods result in better performances and cope with the channel load oscillation problem. Also, TPC CLS achieves better PDR performance if compared with TPC PI. Both the methods do not perform good under random inter-vehicle distances and high mobility.

4.4. Hybrid

Although the purpose of exchanging beacons is to improve vehicle awareness, Aygun et al. [67] stated that the current DCC algorithms does not use awareness as a metric to set transmission parameters. They proposed an Environment and context-aware Combined Power and Rate distributed congestion control (ECPR) which combines TPC with TRC to increase awareness. The simulation results proved that ECPR can be easily built upon current ETSI DCC, and it increases the awareness while keeping channel load under control.

Also Tielert [68] combined message rate control with power control (TPRC), but he evaluated the performance w.r.t. average packet IRT. In this work transmit power is adapted to the target distance, while transmit rate is selected based on the channel load value. Simulation results show that the transmit power can be optimized regardless of the vehicle density. Also, in contrast to pure TPC, TPCR can be easily implemented in real scenarios.

Table 13
Summary table - Transmit Power Control.

Ref.	Methodology	Performance Metrics	Tools
[64]	A TPC method to ensure messages with higher priority have sufficient bandwidth	Probability of beacon reception, message delay **Variation Factor:** Tx-Rx distance, fading environment, D-FPAV configuration, maximum beaconing load.	NS-2
[65]	A TPC method to reduce collisions while ensure the safe time ratio of the application in platooning scenarios	CBR, number of collisions, safe time ratio **Variation Factor:** DCC technique, vehicle density, delay requirement, Tx rate, CCA, platooning leader deceleration.	Cohda Wireless MK2, Unex DCMA-86P
[66]	TCP methods to solve the channel load oscillation problem	CL, PDR **Variation Factor:** Tx-Rx distance, DCC technique.	NS-3, SUMO

Another framework for joint rate and power control in DSRC is designed by Jose et al. in [69]. The authors formulated two optimization problems, named Rate-OPT and Power-OPT: Rate-OPT deals with rate control with fixed transmit power, while Power-OPT deals with power control with fixed rates. Thus, they compared it with the EMBARC method (see Section 4.1) using NS-2 simulator. Numerical results prove that the combination of the two methods outperforms EMBARC in channel utilization and PDR.

The newest thesis by Yongyi et al. [70] is focused on the performance of the Society of Automotive Engineers International DCC (SAE-DCC) [71] and compared it with LIMERIC and PDR-DCC. SAE-DCC adapts message generation rate according to vehicle density and control the transmit power by tacking into account the CBR. LIMERIC and SAE-DCC show very similar results in terms of awareness range, CBR and T-window reliability (i.e. the probability of successfully receiving at least N packets from neighbor vehicles during a time window T). On the contrary, PDR-DCC achieves better performance within 200 m, while LIMERIC and SAE-DCC perform better when distance increases.

Willis et al. [72] proved that in LIMERIC, the Inter Packet Delay (IPD) is often high which makes BSMs unable to reach nodes. The author proposed a new method (OSC Power) to oscillate transmit power between high and low level. In this method, the transmit power is not adapted based on the congestion level like the traditional ETSI DCC. The result shows the hybrid method of OSC Power and LIMERIC can deliver more packets than LIMERIC on its own.

Another hybrid LIMERIC extension is proposed in [73]. Following [62] and [63], Math et al. proposed MD-DCC, which is a combination of TRC and TDC decentralized congestion control. While TRC forces the CL to converge to a given CBP value, TDC is adapted to vehicle density and beacon frequency. In this way, each vehicle maintains the initial transmit rate while reaching the maximum communication range. MD-DCC appears to be more reliable and allows a more efficient channel utilization than LIMERIC, especially in high density scenarios.

Authors in [74] proposed a Multi-Objective Tabu Search (MOTabu) strategy to control congestion in VANETs. Tabu Search is one of the most common used meta-heuristic algorithms which are designed to solve optimization problems [75]. In this work, the Tabu Search algorithm is used to obtain a proper value for transmission range and rate, by minimizing delay and jitter. Due to the high complexity of tuning the transmission range and rate in VANETs, this problem is considered as an NP-hard optimization problem. Tabu Search algorithm is more adaptable and flexible for solving the considered NP-hard problem and the near-optimal values can be obtained for transmission range and rate in reasonable time. Simulation results show that MOTabu strategy significantly outperforms other strategies (e.g., D-FPAV).

4.5. Miscellaneous

Until this point, DCC only considered single hop CAMs (beacons). Kühlmorgen et al. [76] focused on DCC performance for a Contention-Based Forwarding (CBF) algorithm which is a multi-hop forwarding algorithm defined by the ETSI standard. The authors states that the conventional ETSI DCC [77] degrades the performance of CBF under high vehicle density. This is because the DCC entity located at the Access Layer (named DCC_ACC) adds further queuing delay to the overall access layer delay seen by CBF. Therefore, Kühlmorgen et al. extended the ETSI DCC by implementing an additional control based on the received-packet duplication list of CBF. With this solution, when the ITS-S receives a duplicate packet, the DCC instantly drops it. According to the simulation results, the proposed DCC (named DCC Advanced) performs better than conventional ETSI DCC in terms of packet End to End Delay (E2ED), inverse Node Coverage Ratio (NCR) and Data Traffic Overhead (DTO). However, the performance of DCC Advanced for higher priority messages such as CAMs and DENMs has not been investigated.

In 2017, the same authors proposed a novel congestion control algorithm, called Robust Overhearing Recovered Algorithm (RORA) [78]. Previous DCC Advanced method took the next packet one cycle after the detection of packet duplication. The new RORA algorithm instead takes the next packet immediately from the packet queue and doesn't wait for another cycle. Simulation results prove that RORA presents better channel usage than DCC Advanced. Also, by using the novel congestion control algorithm, DENM forwarding results in shorter E2ED and higher Vehicle Converge Ratio (VCR). VCR is the ratio between the number of receiving vehicles and the total number of vehicles located in a given geo-area.

Always for CBF enhancement, Bellache et al. [79] proposed the CBF2C algorithm. CBF2C adapts retransmission count at DCC networking layer. The authors compares CBF2C with conventional flooding and the CBF with Retransmission Threshold (CBF-RT, defined by Kühlmorgen et al. in [80]). Both of these trials are performed with and without DCC. Simulation results show that CBF2C performs better than advanced flooding and CBF-RT in terms of CBR and IRT, especially when DCC is implemented.

Since CBF2C only considered reducing collisions instead of channel load, in [81] the same research group proposed CBF2Cv2. CBF2Cv2 dynamically adapts maximum forwarding delay and the retransmission count threshold based on channel load. Simulation results prove that CBF2Cv2 can further improve performance of CBR and IRT, compared with previous CBF2C.

Another aspect is investigated in [82], where Subramanian et al. observed that the current parametrization for DCC is not suitable

Table 14
Summary table - Hybrid DCC techniques.

Ref.	Methodology	Performance Metrics	Tools
[67]	An environment and context-aware DCC which combines transmit power with rate control to increase awareness (TPC + TRC)	Neighbor awareness, unwanted interference, CBR, Tx rate, Tx power **Variation Factor:** DCC technique, Tx-Rx distance.	GEMV^2
[68]	Transmit power and transmit rate control are combined to improve IRT (TPC + TRC)	IRT, Tx rate, Tx power, goodput **Variation Factor:** Tx rate, Tx power, vehicle density, Tx-Rx distance.	NS-2
[69]	A framework for joint rate and power control in DSRC. The DCC performance is improved if compared with the EMBARC method (TRC + TPC)	Rate of beacon receptions, Tx rate, communication range **Variation Factor:** Tx rate, Tx power, Tx-Rx distance, DCC technique.	NS-2
[70]	SAE-DCC performance evaluation. SAE-DCC outperforms PDR-DCC when Tx-Rx distance is larger than 200 m (TRC + TPC)	CBR, position error, T-window reliability, awareness range **Variation Factor:** vehicle density, Tx-Rx distance, DCC technique.	NS-3, SUMO
[72]	LIMERIC is combined with a TPC method to decrease the packet loss (TRC + TPC)	N. of transmitted messages, PER **Variation Factor:** n. of lanes for edge, DCC technique.	OMNeT++, Veins, SUMO
[73]	LIMERIC is combined with a TDC method to achieve better reliability and channel utilization (TRC + TDC)	CBR, Jain's fairness index, T-window reliability **Variation Factor:** LIMERIC β parameter, Tx-Rx distance, vehicle density, DCC technique.	NS-3, SUMO
[74]	A meta-heuristic algorithm to optimize transmission range and rate (TRC + TPC)	Delay, packet loss, throughput, n. of retransmission for message **Variation Factor:** DCC techniques, vehicle density, mobility scenario.	SUMO, NS-2, MOVE

in many scenarios. In fact, ETSI DCC is compatible with asynchronous IEEE 802.11p, but at the same time it does not take advantage of the periodicity of the safety-critical messages (e.g., CAMs or DENMs). Therefore, Subramanian et al. proposed a Time Division Multiplexing (TDM) built on the IEEE 802.11p MAC layer to avoid the back-off mechanism. The TDM scheme injects packets into the MAC layer at globally synchronized time slots. The proposed technique is then validated through simulation: results show that the synchronous algorithm performs better than asynchronous one in terms of stability and reliability.

The influence of GPS uncertainty on cooperative awareness is instead investigated in [83]. Khan et al. used fusion-based Cooperative Localization (CLoc) to reduce GPS errors, and CLoc data is changed instead of GPS data. It is demonstrated that CLoc provides highly precise awareness.

As in [74], also in [84] a Tabu Search algorithm is used to enhance QoS in VANET. In this work, the authors implement the Tabu Search algorithm with multi-channel allocation capability for scheduling the transmission of queued messages. Thus, they introduce a scheme to prioritize each message considering the message type. The proposed technique is then compared to other methods such as FIFO, EDCA and the so called dynamic scheduling (Dy-Sch). Performance evaluation has been valuated through SUMO simulator and NS-2 and simulation results show the Tabu scheduling is the most efficient.

Scheduling and prioritizing mechanism for VANETs are also discussed in [85]. In the presented strategy, a priority assignment unit assigns priority to each message based on static and dynamic factors. Then, the message scheduling unit reschedules the prioritized messages in the control and service channel queues. The dynamic scheduling step is implemented following two different strategies: *(i)* using the message priorities; *(ii)* using a Tabu Search algorithm (as also proposed in [74] and [84]). The performance of the proposed strategies are investigated in both highway and urban scenarios. Then, both static and dynamic approaches are compared to other existing techniques (e.g. FIFO, EDCA and D-FPAV) achieving better performance in terms of average delay, average throughput, number of packet loss, packet loss ratio and waiting delay in queues.

5. Machine learning applied in congestion control

With traditional methods, operating parameters are set, and adaptively adjusted, based on a deductive approach, that relies on a deterministic and/or statistical model of the system and on measurements of current status. With Machine learning (ML), a heuristic approach is used: the system model is trained based on a large amount of "historical" data collected through previous observations and measurements. This way, operating parameters are adjusted according to knowledge based on experience [86].

ML techniques can be used for different problems in the field of vehicular networks, such as traffic congestion prediction [87], misbehavior detection [88], and the design of multi-hop broadcast protocols for VANETs [89]. Several papers have been recently published, where the main concepts of machine learning and its applications to optimize network performance in dynamic environments [86], [90] are introduced. In this section, we describe some papers that apply ML techniques for congestion control and resource management.

The distributed beacon congestion control strategy proposed in [59] assigns more resources to vehicles having a larger "link weight", in terms of number of neighbors and of respective links qualities. PDR performance is impaired mainly by NLoS conditions, that therefore have to be timely and accurately detected. The authors propose two machine learning methods for real-time identification of NLoS occurrences: Naive Bayes (NB) and Support Vector Machines (SVM). Training is based on "historical" PDR values, observed 1, 5, and 10 seconds before. Accuracy of the method is

Table 15
Summary table - Miscellaneous DCC techniques.

Ref.	Methodology	Performance Metrics	Tools
[76]	An extended ETSI DCC to improve multi-hop CBF performance	E2ED, NCR, DTO, CBR **Variation Factor:** vehicle density, DCC technique.	NS-3
[78]	An extended ETSI DCC to improve CBF performances for high-priority packets	E2ED, VCR, CBR **Variation Factor:** vehicle density, DCC technique.	NS-3, SUMO
[79]	An extended CBF algorithm to achieve better performance when DCC is implemented	CBR, PDR, IRT, n. of duplicate packets **Variation Factor:** vehicle density, DCC enabling.	NS-3
[81]	An extended CBF algorithm: both the maximum forwarding delay and retransmission count are set according to the CL value	Forwarding delay, PDR, E2ED, CBR, n. of duplicate packets **Variation Factor:** vehicle density, CBF algorithm.	NS-3, SUMO
[82]	A TDM approach overlay on top of the IEEE 802.11p MAC layer to bypass the back-off mechanism	RCRP, n. of received packets **Variation Factor:** MAC approach, vehicle density, Tx-Rx distance.	NS-2
[83]	Fusion-based cooperative localization to reduce GPS errors and provide highly precise awareness	IRT **Variation Factor:** Tx-Rx distance, Tx rate, awareness approach (i.e., basic or precise), vehicle density.	Matlab, iTETRIS
[84]	A Tabu Search algorithm is used for scheduling the transmission of queued messages and enhancing QoS in VANET	Delay, packet loss, throughput, Tx rate **Variation Factor:** vehicle density, scheduling approach.	SUMO, NS-3, MOVE
[85]	A dynamic scheduling algorithm is implemented following two different strategies: using the message priorities; using a Tabu Search algorithm	Delay, throughput, packet loss, waiting delay in queue **Variation Factor:** Vehicle density, scheduling approach, IRT, messages (i.e., safety or service), Tx rate, packet queue size.	SUMO, NS-2, MOVE

measured in terms of adherence to the ground truth and of probability of false positives, i.e. that a NLoS occurrence is reported upon LoS conditions. As a result, accuracy of NLoS detection is very good under the different scenarios considered.

Among ML methods, Reinforcement learning (RL) [91] is the most widely used for resource allocation in V2V networking. It allows to satisfy different QoS requirements in a rapidly changing environment, adapting transmission powers and channels allocation, based on parameters such as link quality, interference level, vehicle motion, and so on. Management of network resources through RL, as an alternative to “traditional” optimization techniques, is discussed in detail in [86].

In [92], authors address radio resource allocation methods, remarking the need for careful management of mutual interference between V2V and V2I links, to meet QoS requirements. Most methods are centralized, so they have scalability problems, due to (i) high information sharing overhead, to provide full channel state information (CSI) of links to a central controller (ii) high computational complexity of the optimization algorithm. The authors summarize the state of the art for distributed approaches, that aim to solve these limitations, citing literature works for unicast and broadcast communications. Then they propose a distributed resource allocation method, based on deep reinforcement learning.A decentralized resource allocation mechanism has been proposed for the V2V communications based on deep reinforcement learning for both unicast and broadcast scenarios. Availability of a global information is not required for decision making at each agent, therefore, the transmission overhead is small. A major concern on the deep learning based methods is the computation complexity, but it is not a big issue in this case since the constraint on the vehicles is not very stringent and there are several prior works that reduce the computation complexity of the deep neural networks, such as binarizing the weights of the network [93]. Effectiveness of the method is assessed through simulations, comparing its performance with a random allocation algorithm and a literature method that iteratively assigns transmission sub-bands within groups determined on the basis of similarities.

There are also articles that apply machine learning methods for centralized resource management, such as [94], [95], [96]. According to statistics of road crashes, intersections are critical places for safety, where is then fundamental minimizing collisions due to channel congestion, that is also more likely to occur just in intersections, where the vehicle density is higher. With a centralized approach, the RSU can classify messages according to a clustering algorithm, identify different communication parameters for each cluster to minimize collisions, and broadcast such parameters to vehicles near the road junction.

In [94], the Fuzzy C-means clustering (FCM) algorithm is used. The whole process includes 4 phases: pre-processing, collision detection, data control phase and collision recovery. In pre-processing phase, messages are filtered and then duplicated messages are dropped out. In the collision detection phase, the number of messages in the waiting list is used for collision detection and in the data control phase the flow of data is reduced using the proposed FCM and in the last phase, six different parameters are used for collision recovery. The proposed algorithm has been compared with existing algorithms and it outperforms them in terms of average delay, average throughput, number of packets lost, packet loss ratio and collision probability.

In [95] and [96], messages are classified using k-means machine learning algorithms at each RSU independently. Communication parameters are selected in order to also minimize the transfer delay for each class of messages.

Table 16
Summary table - Machine Learning-based approaches.

Ref.	Methodology	Performance Metrics	Tools
[92]	Satisfying the latency constraints while minimizing the interference of V2V links to V2I links	V2I Capacity, V2V Latency **Variation Factor:** latency constraints.	–
[94]	Fuzzy C-means clustering algorithm is used for clustering of messages in RSU	PDR, packet loss, packet loss ratio and average delay **Variation Factor:** size of the message, validity of messages, distance between vehicles and RSU, message type and direction of the vehicles.	SUMO, NS-3, MOVE
[95]	Applying k-means Machine learning for DCC algorithms to classify the messages at each RSU	Average Delay, Average Throughput, Packets Lost, Packet Loss Ratio **Variation Factor:** message size, message validity, type of messages, direction of the source message, euclidean distance between the source and destination.	SUMO, NS-2, MOVE
[96]	Using k-means clustering algorithm for efficient cluster of messages in RSUs	Average Delay, Average Throughput, Packets Lost, Packet Loss Ratio **Variation Factor:** the message size, message validity, Euclidean distance between the source and destination, type of messages, and direction of the source message.	SUMO, NS-3, MOVE

In [95], the proposed strategy is a centralized and localized strategy because each RSU set at each intersection is responsible for controlling the congestion occurring at that intersection. The proposed method consisted of three units including congestion detection, data control and congestion control units. The congestion detection unit measured the channel usage level to detect congestion. The data control unit collects and filters the messages to remove the redundant messages, and then clusters the messages into four separate clusters using a K-means. The congestion control unit determines communication parameters including transmission range and rate, contention window size and AIFS for each cluster, considering the minimum delay to transfer the messages. At the end, these communication parameters are sent by RSU to the vehicles stopped before red traffic lights to reduce the collision in channels and control the congestion. The performance of this strategy was compared with CSMA/CA [97], D-FPAV [98], CABS [99] and NC-CC [100] strategies and results showed that the proposed strategy outperformed the other congestion control strategies in urban scenarios, in terms of packet loss ratio, average delay and collision probability.

Despite notable progress in many contexts, ML is not ready to be immediately employed in vehicular networks yet, due to some intrinsic characteristics of them. As it is discussed in [86], some open issues have to be addressed, such as: complexity and fast variability of wireless channels, required computational resources, need of distributed learning, coordination and cooperation through information sharing over a capacity-limited network, security. However, the emergence of distributed AI, machine learning and federated learning shows new opportunities for collision control in vehicular environment. See Table 16.

6. Conclusions and future works

This survey paper shows the evolution, as well as strengths and weaknesses, of the DCC mechanism, which is a key feature for DSRC-based vehicular communications. First, the ETSI standardization process on the DCC is described in detail. The paper provides a comprehensive overview on main ETSI DCC limitations together with a focus on the performance evaluation of most known DCC methods. Thus, main techniques proposed in literature to cope with conventional-DCC drawbacks are outlined, such as *(i)* multiple active sub-states mechanism, *(ii)* adaptive parameter setting and *(iii)* cross-layer approaches. After the performance evaluation analysis, the paper continues with a broader state of the art for further DCC techniques, comprehensive of additional TRC, TDC, TPC and hybrid approaches. Also, machine learning methods are addressed with regard to the ability of making DCC techniques more suitable to a dynamic environment. The survey highlights how numerous studies have been conducted with the aim to design an efficient DCC mechanism, but further effort is required to address the congestion control problem in challenging vehicular environments. Especially in both high-mobility and high-density scenarios, the punctual vehicle density estimation is crucial to make DCC more reliable and accurate. In current well-known DCC techniques, as evidenced by this survey, most algorithms estimate vehicle density by calculating number of received beacons from neighbors or by measuring channel load. However, under critical traffic scenarios, these methods are not effective and more accurate measurement methods are needed. Further, other challenges may come from interoperability issues between different standards. As described in the previous sections, many approaches based on DCC, such as TPC, TRC, and TDC, have been formalized and standardized by ETSI. However, ETSI DCC is not suitable to co-exist with other beaconing protocols (e.g., slotted and dynamic) and more research efforts are still needed about combinations of different algorithms. Also, MAC layer design has to be considered, since different V2X standards lead to different MAC approaches (e.g., TDMA, SDMA and CSMA). Last, further improvement can be achieved in DCC validation both in simulation environments and through experimental analysis on real devices. To the best of our knowledge, a large number of research projects are focused on simulation and numerical results analysis, while the literature is lacking with regard to the experimental results coming from on-field trials. In the near future special attention is to be given to the on-field experimentation and also to the hardware-in-the loop approaches, to better analyze and characterize the great variety of road environments.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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