An Insight into Decentralized Congestion Control Techniques for VANETs from ETSI TS 102 687 V1.1.1

Alessia Autolitano[†], Claudia Campolo[*], Antonella Molinaro[*], Riccardo M. Scopigno[†], and Andrea Vesco[†]
[†]Istituto Superiore Mario Boella, Turin, Italy
E-mail: surname@ismb.it
[*]Università Mediterranea di Reggio Calabria, Italy
E-mail: name.surname@unirc.it

***Abstract*—Many cooperative applications designed to improve road safety rely on the frequent exchange of awareness messages among vehicles. Therefore, under high vehicle density, the channel medium is expected to get congested. To tackle this situation, the European Telecommunications Standards Institute (ETSI) specified a set of Decentralized Congestion Control (DCC) mechanisms that adapt the transmission parameters based on channel load measures. Due to some concerns about its effectiveness and stability, DCC and its overall philosophy are currently being revised and extended: all in all, DCC deserves additional investigations.**

For this purpose, in this paper a simulation analysis is presented, aiming at enriching the insight into the DCC behaviour, under a variety of channel load conditions and through the definition of both link- and application-layer performance metrics. Achieved results show that the DCC techniques are not really effective with the currently specified parameters settings; hence some hints are given to improve their performance.

***Index Terms*—CAM, congestion control, DCC, ETSI, VANET**

I. Introduction

Over the last few years the interest in Intelligent Transportation Systems (ITS) has grown rapidly from academia, governmental agencies, automotive and electronic industries. A wide range of ITS services, spanning from safety alerting to traffic efficiency and management, can be provided through Vehicular Ad hoc NETworks (VANETs). Stakeholders both in USA and in Europe are struggling to finalize standards for VANETs, in order to define transport and forwarding routines, efficient channel access mechanisms, scalable and reliable transmission procedures that are resilient to channel errors, fast nodes and high traffic density.

Congestion control is one of the main challenges, since the medium can easily get congested due to the massive local exchange of *status* messages among vehicles. They are referred to as Cooperative Awareness Messages (CAMs) in Europe [1] and are regularly transmitted (with a frequency ranging from 1 to 10 Hz) to provide information of a vehicle presence, position and basic status to one-hop neighbours.

Keeping channel congestion under control is crucial to guarantee the *reliable* and *timely* exchange of CAMs. This represents the milestone for a widespread deployment of cooperative vehicular applications aimed at enabling a timely and safely driver support (e.g., during lane changing and intersection crossing).

Recently, ETSI has specified a set of Decentralized Congestion Control (DCC) mechanisms [2] that adapt transmission parameters to keep the channel load below pre-defined thresholds. Despite the proliferation of works addressing congestion control (by adapting the transmission power as in [3], [4], the packet transmission interval [5]-[8], or jointly the two parameters [9]), to the best of our knowledge, just a few works [10], [11] have specifically investigated the standardized DCC performance in a systematic way; additionally, a separate characterization of each DCC mechanism, so to understand their respective points of strength and weaknesses, is still missing. These constitute the main goals of this study.

In more detail, the main contributions of this paper are:

- a detailed performance evaluation of the DCC mechanisms specified in [2], under variable channel load conditions: the transmission parameters adaptation mechanims that we judge as the most valuable ones are *together enabled* in evaluating the DCC scheme and *individually* analyzed to understand if and to which extent they affect the overall DCC performance;
- a comparison of the DCC schemes against the legacy IEEE 802.11p [12] without congestion control schemes;
- a performance assessment of the above mentioned techniques based on both *link-* and *application-layer* metrics;
- a final discussion introducing some hints for the possible future improvement of DCC performance.

Notably, such contributions are particularly relevant at this stage of DCC deployment: in fact, since the overall DCC is being re-discussed (see Section II), a deeper insight into DCC, by extensive simulation results, is vital to revise it as best as possible.

II. The ETSI DCC mechanisms

The protocol architecture of an ITS station specified by ETSI foresees: the *Security*, *Facilities*, and *Networking & Transport* layers, respectively encompassing tasks related to security and privacy, addressing and routing, network and transport, and multi-channel usage, and the *Access* layer, including the ITS-G5 physical (PHY) and medium access

978-1-4799-0543-0/13/$31.00 ©2013 IEEE

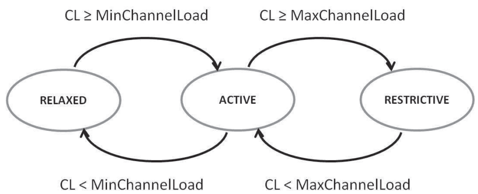

Fig. 1. The DCC state machine according to ETSI TS 102 687 v1.1.1 [2]

control layer (MAC), the European counterpart of 802.11p, specified as one of the possible access technologies [13].

The Carrier Sense Multiple Access scheme at the basis of the MAC layer may suffer from collisions, unfair resource allocation, and unbounded channel access delay, when the number of nodes increases. These effects are especially adverse for the performance of safety applications that rely on the timely and reliable exchange of CAMs among vehicles on the common control channel (CCH) [13]. To counteract such issues ETSI has specified the DCC architecture as a mandatory component of an ITS-G5 station. It spans across the ITS station layers as follows: *(i)* the *DCC-Access* [2] acts on parameters at PHY and MAC layer and is being amended by the Specialist Task Force (STF) 420; decisions on its evolution are still pending; *(ii)* the *DCC-Net* [15] is logically at network (and transport) layer: it is being studied by STF 447, with the aim of mapping the traffic classes of CAM messages (as generated by the Facility Layer) to DCC profiles (which will act on power and rate); *(iii)* the *DCC-Facility* [16] will act on CAM and Decentralized Environmental Notification Message (DENM) generation and profiles; *(iv)* the *DCC-Management*, finally, will be a Cross Layer Entity, whose purpose is the inter-operation between the different layer-specific DCC entities, and to manage all DCC functionalities (including DCC parameter control), so to come to a stable and effective cross-layer framework; a STF is being launched (planned for the end of 2013) to support it.

Despite the mushrooming DCC standards, so far DCC-Access is the only which has been defined [2]: its assessment constitutes the objective of this study. Basically, DCC-Access aims at controlling congestion by acting on transmission parameters, with no changes in the channel access scheme. The following mechanisms have been standardized:

- TPC (Transmit Power Control) that adapts the transmission power P_t;
- TRC (Transmit Rate Control) that adapts the interval between transmitted packets;
- TDC (Transmit Datarate Control) that adapts the packet transmission data rate;
- DSC (DCC Sensitivity Control) that adapts the Clear Channel Assessment (CCA) sensitivity threshold $CSThresh$, providing a busy channel indication during the packet reception;
- TAC (Transmit Access Control): that dynamically opens and closes the access of packets with a given priority to the related transmit queue.

All the mechanisms rely on the state machine in Figure 1 that distinguishes three states, *relaxed*, *active*, and *restrictive*, in increasing order of channel congestion. DCC is a completely decentralized approach; state transitions are driven by the channel load (CL) conditions locally measured by each node during a sampling interval, T_m. The CL is computed as the fraction of time during which the received signal is above the CCA threshold (i.e., the channel is sensed as busy). $MinChannelLoad$ is the minimum CL below which the channel is practically free and the DCC state will be *relaxed*; $MaxChannelLoad$ is the maximum CL above which the channel is considered overloaded and the DCC state will be *restrictive*. A transition from *relaxed* to *active* and from *active* to *restrictive* occurs if the minimum CL measured over the last T_{up} period is higher than the $MinChannelLoad$ and the $MaxChannelLoad$ threshold, respectively. Whereas a transition from *restrictive* to *active* and from *active* to *relaxed* occurs if the maximum CL measured over the last T_{down} period is lower than the $MinChannelLoad$ and the $MaxChannelLoad$ threshold, respectively.

III. Motivations and Objectives

Despite the valuable objectives of the DCC techniques specified by ETSI, so far just a few works have investigated their performance. In [10] DCC mechanisms are *all simultaneously* enabled and results show that they are not successful in controlling congestion and ensuring reachability. Then, the authors propose enhancements to the TPC technique: a state machine is designed with six states and with a higher channel load threshold for the congested state. A comprehensive and valuable study of the DCC scheme is also reported in [11] that strictly follows the current parameters set suggested in the standard. Both works do not distinguish the effects of *each single mechanism*. In [6] the authors evaluates the TRC technique that is also compared against their own solution.

In this paper we intend to take a step forward by providing a comprehensive analysis of the set of DCC mechanisms that we consider more suitable for cooperative safety applications. Focus is on the TPC, DSC and TRC techniques. TDC is not evaluated because there is a wide consensus on fixing 6 Mbps as the transmission data rate for safety messages [17]. TAC is not considered because adapting the queue settings is more indicated to handle prioritization between different types of traffic, which is outside the scope of the paper.

In our study, unlike previous works, we compare the *single DCC mechanisms* in order to get insights on the impact of each transmission parameter adaptation mechanism on the overall DCC performance. For the sake of completeness, the DCC scheme where TPC, TRC and DSC are simultaneously active is also evaluated. All such schemes are compared against the *legacy* solution where the 802.11p MAC layer is not provided with congestion control mechanisms. The comparison is based on a set of performance metrics specified to evaluate the effectiveness and stability of the analysed techniques. The study also aims at providing suggestions about possible enhancements to the currently specified DCC policies and settings. Last but not least, a final comparison among the current DCC mechanisms is provided (Table IX): this is indeed a distinctive result, primarily meant to facilitate the revision of DCC-Access mechanisms, especially under the hypothesis of selecting only a subset of the available mechanisms [14].

TABLE I
SIMULATION PARAMETERS

Category	Parameter	Value
PHY	Frequency/Channel bandwidth	5.9 GHz/10 MHz
	Propagation	Nakagami (m=3)
	Power monitor threshold	-102 dBm
	Noise floor/CSThresh/P_t	-99 dBm/-95 dBm /23 dBm
MAC	Slot/SIFS time/Header length	13 μs/32 μs/40 μs
DCC	T_m, T_{up}, T_{down}	1s, 1s, 5s
	$MinChannelLoad$	0.15
	$MaxChannelLoad$	0.4

TABLE II
DCC PARAMETERS

Scheme	Metric	RELAXED	ACTIVE	RESTRICTIVE
TPC	P_t	33 dBm	15 dBm	-10 dBm
DSC	$CSThresh$	-95 dBm	-85 dBm	-65 dBm
TRC	Packet interval	0.04s	0.5s	1s

IV. PERFORMANCE EVALUATION

Performance has been evaluated through *ns*-2 simulations. A new software module has been developed that cooperates with the overhauled PHY and MAC layers [18]; it implements the DCC mechanisms that are fully compliant to the ETSI standard [2]. Vehicles are randomly placed in a 750m-wide *grid* of 6 x 6 double-lane roads, spaced 150m apart. They are tuned to the CCH to exchange CAMs at every 100 ms. The offered traffic is varied by changing the packet size (100 and 300 bytes) and the number of vehicles (300 and 600) in the grid. Contention window (CW) is set equal to 15 to leave access categories with shorter CWs and AIFSs to higher priority safety messages.

The main simulation parameters, set according to standard specifications, are summarized in Table I. The parameters of each considered DCC scheme are reported in Table II.

A. Performance metrics

The DCC performance is evaluated against the *legacy* scheme in terms of the following metrics: *(i)* the *packet delivery ratio* (PDR), *(ii)* the *update delay*, *(iii)* the *channel load* averaged over all nodes during the overall simulation, computed as described in Section II. The PDR accounts for *reachability* and is computed as the percentage of nodes receiving a data frame at a given distance from the transmitter in the range 0-400m. The update delay, as proposed in [4], is defined as the time difference between two consecutive successfully received CAMs from the same transmitter. It describes the *up-to-dateness* of status information from the surrounding vehicles in an awareness range (AR): the higher the update delay, the longer no CAM has been received. Results are shown for update delays computed over the neighbors in a range of 400 m and 50 m. Indeed, the most important statistics are those within the first meters, where the successful reception is fundamental for safety messages.

In order to go deeper into the DCC mechanisms performance, further metrics are specifically considered: the *percentage of nodes* in each DCC state; the *average permanence time* in each state between two switching events; the *average number of state switching events* per node per minute.

B. Simulation Results

The PDR results are illustrated in Figures 2 as a function of the distance between transmitter and receiver. The performance of all schemes gets worse *(i)* as the packet size increases for a given number of vehicular nodes, due to the longer packet transmission times and the resulting longer channel busy times, and *(ii)* as the node density increases, when fixing the packet size, due to higher contention and collisions.

As a general remark, under low-to-medium traffic conditions it can be noticed that the legacy scheme outperforms the other mechanisms over the entire range, with the exception of the first meters where TPC, TRC and DCC achieve slightly higher PDR values. Then, despite the potential reduction of transmission attempts, the TRC scheme behaves worse than the legacy mechanism. Packets generated by the application layer at every 100 ms, pile up in the MAC queue in the active state (when they are transmitted every 500ms) and when switching back to the relaxed state they are attempted to be transmitted every 40ms, hence increasing the probability of collisions and congestion.

PDR values for TPC heavily shrink as the transmitter-receiver distance increases. This is mainly due to the low transmission power (15 dBm) in the active state that reduces the area covered by the message.

Even DSC achieves slightly lower PDR values than the legacy scheme. In fact, as shown in Table VII, the majority of the nodes stay in *active* state, where the CCA threshold for DSC is higher than the one in the legacy scheme. As a result, a node is less sensitive to other transmissions, it is blocked less often, but the collision probability increases.

DCC combining all adaptation mechanisms exhibit PDR values worser than each single technique. This is because, it inherits the main weaknesses of each scheme.

Under heavier traffic conditions, when considering a packet size equal to 300 bytes and 600 nodes, differences among the compared schemes get more remarkable. TPC exhibits the poorest performance, with unacceptable PDR values, due to low transmission power values in the active and restrictive states that significantly reduce the communication range. Under heavier congestion, DSC further increases the carrier sense threshold and consequently the collision probability increases, for motivations explained above.

The better performance of the TRC scheme with the increase in the traffic load could be misleading. Even if the percentage of successfully received packets is higher, it is computed on a very low number of transmitted packets. In fact, when congestion is detected, the packet interval is significantly increased to 500ms and then to 1s. In the case with 600 nodes and 300bytes-long packets, with TRC each node transmits nearly 2 packets/s instead of the 10 packets/s of the legacy scheme.

Results in Tables III and IV show the update delay metric and demonstrate that in the $AR = 50$ m case, all schemes, with the exception of TRC and DCC, are able to guarantee

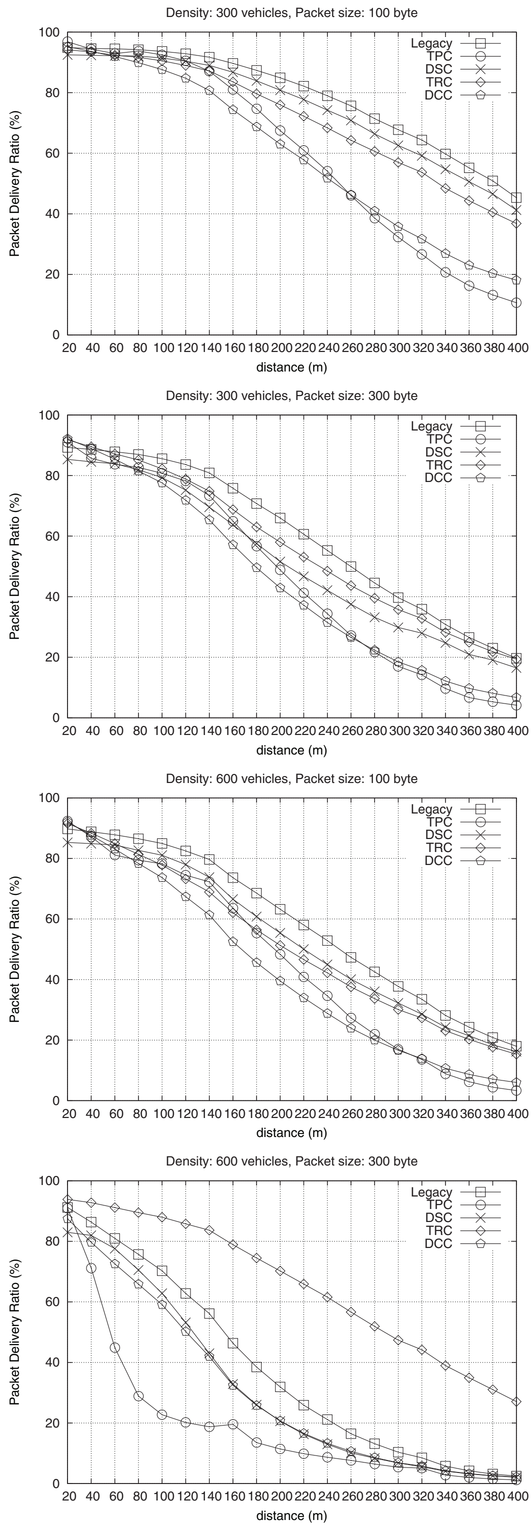

Fig. 2. Packet delivery ratio at different transmitter-receiver distances when varying the packet size and the node density in the grid

an update delay close to 100 ms, regardless of the packet size and the number of vehicles. The update delay increases over the range 0-400m, with the legacy scheme confirming its superiority in terms of reliability and up-to-dateness of exchanged information, and with TRC and DCC reporting the

TABLE III
UPDATE DELAY (S), 300 VEHICLES

Scheme	Packet size=100 bytes		Packet size=300 bytes	
	AR=400m	AR=50m	AR=400m	AR=50m
Legacy	0.216	0.105	0.308	0.112
TPC	0.366	0.105	0.368	0.114
DSC	0.230	0.108	0.36	0.117
TRC	0.603	0.267	0.959	0.311
DCC	0.878	0.279	1.348	0.314

TABLE IV
UPDATE DELAY (S), 600 VEHICLES

Scheme	Packet size=100 bytes		Packet size=300 bytes	
	AR=400m	AR=50m	AR=400m	AR=50m
Legacy	0.318	0.112	0.465	0.114
TPC	0.384	0.114	0.595	0.138
DSC	0.351	0.117	0.552	0.122
TRC	1.011	0.311	1.242	0.542
DCC	1.387	0.306	1.668	0.364

worst results. This is to be ascribed to the increased packet transmission interval for TRC. Under congestion TRC is not able to support cooperative safety applications requiring timely CAM updates, since it hinders nodes to receive CAMs from their neighbors at every 100ms, even from the closest ones. DCC behaves even worse because it applies simultaneously TPC and TRC mechanisms, hence the update delay is negatively affected both by the high packet loss in TPC and the lower number of packets transmitted in TRC.

As regards the channel load values in Table V, they increase with the number of nodes and the packet size, due to higher channel congestion. This is the trend of each scheme, with the exception of TPC, for which, interestingly, under crowded conditions the load decreases because of the enforced strong transmission power reduction. The legacy and DSC schemes exhibit channel load values close to 0.68 under high node density. In TPC, TRC and DCC, nodes measure significantly lower channel load values, even under high traffic densities and large packet sizes. However, the motivations behind such a similar trend are completely different. In TPC the lower channel load is due to the use of a very low transmission power value (-10 dBm) by nodes in the restrictive state. TRC, instead, reduces the number of transmissions, by increasing the packet transmission interval under congestion. Such an apparent benefit is paid in terms of a higher update delay, as discussed before. DCC benefits from both approaches in terms of channel load reduction, although it does not improve the overall reliability and timeliness performance.

C. More details on DCC mechanisms

Results in Tables VII and VIII show that TPC, TRC and DCC are the least stable schemes. With TRC and DCC, nodes continuously switch between active and restrictive states: nearly 10 switching events per node per minute and a very short average permanence time in active and restrictive states (nearly the time required for a transition up, 1s, and a transition

TABLE V
AVERAGE CHANNEL LOAD

Scheme	Packet size=100 bytes		Packet size=300 bytes	
	300 vehicles	600 vehicles	300 vehicles	600 vehicles
Legacy	0.203	0.392	0.442	0.677
TPC	0.119	0.177	0.213	0.154
DSC	0.202	0.389	0.422	0.684
TRC	0.078	0.123	0.139	0.168
DCC	0.075	0.102	0.116	0.156

TABLE VI
NUMBER OF SWITCHING EVENTS PER NODE PER MINUTE

Scheme	Packet size=100 bytes		Packet size=300 bytes	
	300 vehicles	600 vehicles	300 vehicles	600 vehicles
TPC	9.95	4	2.63	10
DSC	0.16	0.65	0.76	1
TRC	9.67	10	10	7.08
DCC	10	10	10	9.99

down, 5s) are experienced under low-to-medium congestion. Lower instability is experienced by TPC under medium load conditions. Such instability is due to the fact that when switching between active and restrictive states, nodes drastically change their transmission parameters, i.e., transmission power and packet interval for TPC and TRC, respectively. Therefore, the channel load is significantly reduced and makes nodes switching to a less congested state and, then, from it to a more congested one since the channel gets soon congested again.

DSC lets a large fraction of nodes stay in restrictive state, when 300 bytes are considered. As a matter of fact, once a node enters the restrictive state, it remains there. Such a behaviour is witnessed by the low number of switching events among states (the highest value is one switching per minute) in Table VI, and by the long average permanence time in a given state in-between switching events in Tables VII and VIII.

D. *On the effect of tuning DCC parameters*

Achieved results show that TRC outperforms the other approaches in terms of reachability, especially under highly crowded scenarios, but at the expenses of a long update delay even in the first meters, which may be intolerable for some applications. The other schemes behave even worse than the legacy approach, hence questioning about the suitability of DCC parameters settings, judged to be too conservative, and the effectiveness of some proposed techniques, e.g., DSC.

To support such claims, results are reported in Figure 3 that have been collected in the scenario with 600 nodes and 300bytes-long packets when modifying the settings of some of the parameters specified in [2] for the TRC and TPC schemes, the ones that mainly affect the overall DCC behaviour. The latter ones proved to be effective in keeping low the channel load, but they may not satisfy applications requirements. In particular, results are collected when the transmit power of -10dBm in the restrictive state [2] is replaced by 5dBm.

Regarding the TRC scheme, the packet interval of 40ms in the relaxed state specified in [2] proved to be too short

TABLE X
UPDATE DELAY (S), 600 VEHICLES, 300 BYTE

Scheme	AR=400m	AR=50m
Legacy (PTI=0.1s)	0.465	0.114
Legacy (PTI=0.2s)	0.57	0.224
DCC	1.668	0.364
TPC+TRC	0.73	0.223

and generate more collisions than the legacy scheme. Values in the other states, instead, force nodes to heavily reduce the packet transmission frequency. Results in Figure 3 show that the TRC setting (PTI_{REL}=0.1s, PTI_{ACT}=0.2s, PTI_{RES}=0.3s) coupled with the mentioned TPC modified transmission power value, with no DSC enabled (curve labelled as TPC+$TRCmod$) provide higher PDR values and, even, lower update delay values, Table X, albeit still higher than the legacy scheme. For the sake of completeness, results are also compared with the legacy scheme foreseeing the application generating packets at every 200 ms (instead of 100ms, resembling the worst case traffic generation pattern), hence halving the number of generated packets and, consequently, the channel load. The proposed settings lead to better PDR values in the first 100m and have the additional advantage of dynamically adapting the transmission parameters according to the experienced channel load and not forcing them in a static way.

V. CONCLUSION

In this paper we have conducted a study aimed at deeply investigating the performance of DCC mechanisms as currently specified by ETSI. The main findings are summarized in Table IX. TRC and TPC are the mechanisms that mainly affect the overall behaviour of the DCC scheme and achieved results show that they are highly sensitive to their adaptation parameter settings. Timing and CL threshold parameters should be carefully set to reduce the switching events between states, resulting in fluctuations in the experienced channel load and instability of the schemes. CL measurements could be a further limitation and affect the DCC stability. State transitions from a less congested to a more congested state rely on *instantaneous* CL values. A more reliable estimation could help to filter out transient effects in load values. It could be useful even for the transitions from a more congested to a less congested state. In addition, the *binary* CL measurement (it only gives an indication about the fact that channel is detected as busy or not in a given instant) could be replaced with a more accurate metric that accounts for *how much* the channel is perceived as busy. All in all, the conducted analysis identifies several aspects that deserve further investigation in order to improve the overall DCC performance and that require tighter correlation with the application requirements for parameters tuning in order to achieve the desired outcomes. Simulations under different road topologies and parameters settings will be a subject matter of future work.

TABLE VII
NODES PERCENTAGE AND PERMANENCE TIME PER DCC STATE (300 VEHICLES)

Scheme	Packet size=100 bytes			Packet size=300 bytes		
	RELAXED	ACTIVE	RESTRICTIVE	RELAXED	ACTIVE	RESTRICTIVE
TPC	8.05%-1s	88.14%-8.68s	3.81%-8.98s	3.66%-6.65s	87.08%-11.02s	9.25%-8.99s
DSC	18.48%-5.98s	81.52%-24.78s	0-0	0-0	37.93%-1.48s	62.07%-55.58s
TRC	12.65%-1.55s	87.35%-8.99s	0-0	8.47%-1s	91.53%-8.99s	0-0
DCC	8.47%-1s	91.53%-8.99s	0-0	8.47%-1s	91.53%-8.99s	0-0

TABLE VIII
NODES PERCENTAGE AND PERMANENCE TIME PER DCC STATE (600 VEHICLES)

Scheme	Packet size=100 bytes			Packet size=300 bytes		
	RELAXED	ACTIVE	RESTRICTIVE	RELAXED	ACTIVE	RESTRICTIVE
TPC	2.12%-1s	84.18%-15.16s	13.6%-8.97s	1.64%-1s	31.95%-3.59s	66.4%-8.86s
DSC	0-0	51.51%-1.82s	48.49%-54.41s	0-0	1.69%-1s	98.31%s-57.95s
TRC	8.47%-1s	91.53%-8.99s	0-0	2.13%-1s	51.8%-6.49s	46.07%-8.98s
DCC	8.47%-1s	91.53%-8.99s	0-0	8.44%-1s	91.26%-8.97s	0.30%-8.97s

TABLE IX
SUMMARY OF THE MAIN FEATURES OF THE ANALYZED DCC SCHEMES

	Adapted parameter	Reachability	Up-to-dateness	Stability	Channel load
TPC	Transmission Power (TP)	Very low	Medium	Low	Low
DSC	Carrier Sense Threshold (CST)	Low	Medium	High	High
TRC	Packet Transmission Interval (PTI)	High	Low	Low	Low
DCC	TP+CST+PTI	Medium	Low	Low	Very low

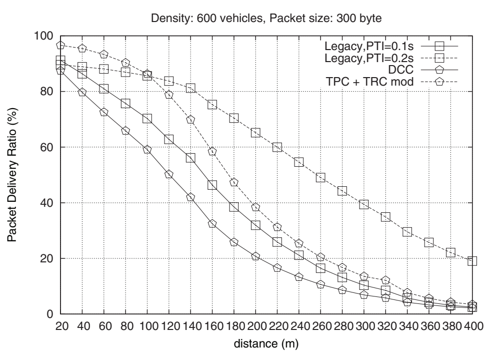

Fig. 3. Packet delivery ratio at different transmitter-receiver distances under different settings for legacy and DCC schemes

ACKNOWLEDGEMENTS

The European project GLOVE (joint GaliLeo Optimization and VANET Enhancement G. A. 287175) has supported the activities leading to the results here presented. GLOVE aims at identifying VANETs weaknesses and at mitigating them by leveraging the time-space information provided by Galileo (WP1, WP2). The authors thank ETSI, for the fruitful discussions of results at the meeting ITS WG4-24 (June 2013).

REFERENCES

[1] ETSI EN 102 637-2, "ITS; Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service," June 2012.

[2] ETSI TS 102 687 V1.1.1, "Intelligent Transport Systems (ITS); Decentralized Congestion Control Mechanisms for Intelligent Transport Systems operating in the 5 GHz range; Access layer part," July 2011.

[3] M. Torrent-Moreno, et. al., "Vehicle-to-vehicle communication: fair transmit power control for safety-critical information," *IEEE Trans. on Vehi. Tech.*, vol. 58, no. 7, pp. 3684-3703, 2009.

[4] B. Kloiber, et. al., "Dice the TX power - Improving awareness quality in VANETs by random transmit power selection," In *IEEE VNC*, 2012.

[5] C. Sommer, et. al., "Traffic Information Systems: Efficient Message Dissemination via Adaptive Beaconing," *IEEE Comm. Mag.*, vol. 49, no. 5, pp. 173-179, 2011.

[6] C. Sommer, et. al., "How Shadowing Hurts Vehicular Communications and How Dynamic Beaconing Can Help," In *IEEE INFOCOM*, 2013.

[7] J. Kenney, et. al., "LIMERIC: A Linear Message Rate Control Algorithm for Vehicular DSRC Systems," In *IEEE VNC*, 2011.

[8] T. Tielert, et. al., "Design Methodology and Evaluation of Rate Adaptation Based Congestion Control for Vehicle Safety Communications," In *IEEE VNC*, 2011.

[9] L. Le, et. al., "Performance Evaluation of Beacon Congestion Control Algorithms for VANETs," In *IEEE GLOBECOM*, 2011.

[10] S. Subramanian, et. al., "Congestion Control for Vehicular Safety: Synchronous and Asynchronous MAC Algorithms," *ACM VANET* 2012.

[11] D. Eckhoff, N. Sofra, R. German, "A Performance Study of Cooperative Awareness in ETSI ITS G5 and IEEE WAVE," In *IEEE WONS 2013*.

[12] "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications" IEEE, Standard 802.11-2012.

[13] C. Campolo, A. Molinaro, "Multichannel Communications in Vehicular Ad Hoc Networks: A Survey," *IEEE Comm. Magazine*, vol. 51, no. 5, pp. 158-169, 2013.

[14] J. de Jongh, "Geo-Networking Media-Dependent Functionality for ITS-G5", ETSI ITS Workshop, 5-6 Feb. 2013, Austria, Vienna.

[15] DRAFT ETSI TS 103 141 "Intelligent Transport Systems; Facilities layer; Communication congestion control," 2013.

[16] DRAFT ETSI TS 102 636-4-2, "Intelligent Transportation Systems (ITS); Vehicular Communications; Part 4: Geographical Addressing and Forwarding for Point-to-Point and Point-to-Multipoint Communications; Sub-part 2", 2013.

[17] J. Daniel, Q. Chen, and L. Delgrossi, "Optimal data rate selection for vehicle safety communications," In *ACM VANET* 2008.

[18] Qi. Chen, et al. "Overhaul of IEEE 802.11 Modeling and Simulation in NS-2," ACM MSWiM 2007.