Investigating the Effectiveness of Decentralized Congestion Control in Vehicular Networks

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***Abstract*—Vehicular ad hoc networks are expected to suffer from channel congestion, due to the high number of vehicles moving on the roads, the limited available bandwidth and the many applications that they will support. In order to mitigate such problem, ETSI has recently specified the Decentralized Congestion Control (DCC) mechanisms for Intelligent Transportation Systems (ITS) operating in the 5 GHz range. Although they are already part of the standard, very few results exist on the DCC performance. In this work, we aim at filling this gap by investigating the impact on the system performance of the single DCC mechanisms, as well as their joint effect when they are all implemented at the DCC access layer. Surprisingly, we find that DCC has little impact, and, in certain scenarios, it may even lead to performance degradation with respect to the case where the legacy IEEE 802.11p MAC protocol is implemented.**

I. INTRODUCTION

Vehicular ad hoc networks (VANETs) will enhance traffic safety, for both in-vehicle passengers and other road-users, through a diverse set of applications. Most of such applications require real time communication, with strict constraints, not only on the message delivery delay, but also on the message transfer reliability. In addition, they often relay on broadcast message transmissions, for which it is important to ensure a good level of scalability.

According to the ongoing standardisation, traffic safety applications in VANETs rely on the IEEE 802.11p specifications, which introduce a distributed channel access scheme based on the CSMA/CA technique. It is well-known that the CSMA/CA mechanism provides a fair channel access to the contending nodes, i.e., on average, it lets nodes access the channel the same number of times in a given time period. However, in the short run, it is an inherently unpredictable protocol: the random exponential backoff procedure may lead to unbounded channel access delays, interference between concurrent transmissions may end up into transmissions failures, and messages, whose transmission fails repeatedly, have to be dropped. Such problems arise especially when there are several nodes contending for the wireless medium, thus highlighting the poor scalability of the mechanism.

In order to mitigate the above problems, ETSI has recently standardised the so called Decentralized Congestion Control (DCC) [1] whose goal is to let the network work as efficiently as possible, achieving high throughput while maintaining low packet loss and delay. For the sake of precision, DCC is currently being amended at access layer and extended to other layers[1], leading to the definition of a *cross-layer* DCC function. Concerning the upcoming amendments, it seems that they will deeply reduce the mechanisms at access layer and borrow some of the ideas proposed in [4], with the aim of counteracting the poor effectiveness of current algorithms, accordingly to what will presented here.

However, to this end, DCC leverages the local (ego-vehicle's) knowledge about the channel status so as to trigger adjustments to the parameters characterising the node transmissions, thus reducing channel congestion. The channel state information is acquired using channel probing, and the obtained measurements are used to enable the following mechanisms:

- Transmit Power Control (TPC), controlling the average transmit power per packet;
- Transmit Rate Control (TRC), varying the node transmission duty cycle, i.e., the fraction of time during which a node is in "transmit" state;
- Transmit Data-rate Control (TDC), determining the data rate used by the node to transmit its packet;
- DCC Sensitivity Control (DSC), adapting the clear channel assessment to resolve local channel congestion;
- Transmit Access Control (TAC), introducing a transmit queueing concept to handle packet priority.

Currently, few works have investigated how much effective the DCC mechanisms are mitigating traffic congestion and whether they are stable. For instance, in [5] the authors focus their analysis of DCC on the TPC mechanism only, which is shown to lead to poor performance due to the coarse settings defined in the standard [1]. This indeed highlights the need for more extensive analyses so as to delve into the underlying phenomena of the overall DCC – not just TPC – and to pinpoint its potential weaknesses. Despite DCC will be shortly redefined, the proposed analysis intends to draw conclusions on the current DCC, hopefully supporting the analysis of future embodiments.

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[1] The worry about congestion is such that different layer-specific DCC entities have been defined to prevent and counteract the effects of congestion. The DCC_Access [1], being amended by the Specialist Task Force STF420, acts on parameters at physical and MAC layer to lower the load; the DCC_Net [2], at network and transport layer is being studied by STF447 to map the traffic classes of CAM messages, generated by the Facility Layer, to DCC profiles acting on power and rate; finally DCC_Facility [3] which acts on CAM / DENM generation.

In our work, we therefore implement the current DCC mechanisms in the widely-used network simulator *ns*-2 and study, separately, the impact of each of the aforementioned mechanisms as well their joint effect when they are all triggered at the same time. We show the system behaviour in terms of packet delivery ratio (PDR) as well as channel access delay. Our results suggest that, as it is currently envisioned, the DCC mechanism has low impact on the system performance and, in many cases, it is unable to reduce channel congestion. The analysis of the single mechanisms also highlights two important facts. Firstly, some of the DCC mechanisms may be particularly effective, but their advantage vanishes when they are all triggered at the same time, as they often favour opposite system behaviors. Secondly, other DCC mechanisms do not have any significant impact when implemented with the default settings, i.e., as suggested by the standard specifications; however, they could play a major role if different setting could be used.

The rest of the paper is organised as follows. Section II summarises the DCC mechanisms, specifying their goal and the way they should be implemented. Such mechanisms are then investigated through simulation in the scenarios described in Section III. Their performance, when they are separately and jointly activated, is presented in Section IV. Finally, we draw our conclusions in Section V.

II. THE DCC MECHANISMS

As mentioned, the current DCC acts at several layers of the protocol stack, through mechanisms that are jointly activated to (*i*) achieve fair allocation of resources among all nodes operating in the same geographical area, (*ii*) keep the channel load low, (*iii*) provide fast adaptation to the surrounding, highly-dynamic environment.

Two important DCC components are located at the management and access layers. The former is responsible for setting the parameter values that are used for configuring the access component, specifically, their minimum, maximum, default and target values, as well as signal level thresholds and time constants. The latter enhances the 802.11p MAC architecture, by adding four blocks:

1) Transmit Queuing, which enhances the standard 802.11 queues by DCC mechanisms;
2) Channel Probing, collecting statistics on the communication channel and assessing the channel load. Measurements are taken based on the power detected on the channel and on the physical header of the packets over the medium, which depend on the DCC Sensitivity (NDL_defDCCSensitivity);
3) Transmit Statistics, which takes into account all transmitted packets, including retransmissions and control packets. For each access priority, it yields statistics such as the packet arrival rate at the transmit queue, and the average transmission duration and power level.
4) Control Loop, which adapts the behavior of the ITS node to the estimated channel load, by properly setting the reference value of transmit power (NDL_refTxPower), packet interval (NDL_refPacketInterval), data rate (NDL_refDataRate), CCA sensitivity (NDL_refCarrierSense), and queue status; such parameters are then used by the DCC mechanisms (i.e., TPC, TRC, TDC, DSC and TAC).

The DCC access blocks act as follows. Once the measurements on channel load are made available by the Channel Probing block, the Control Loop sets the channel state to *Relaxed* if the channel load is below a minimum threshold (NDL_minChannelLoad) specified by the DCC management layer, to *Restricted* if it is above a maximum threshold (NDL_maxChannelLoad), and to *Active* otherwise. While in Relaxed state, the reference transmit power level is set to the maximum value while the reference transmit interval, data rate and CCA sensitivity are set to their minimum. On the contrary, when in Restricted state, the reference transmit power level is set to the minimum, while the reference transmit interval, data rate and CCA sensitivity to their maximum. Indeed, the higher the CCA sensitivity value that is used, the higher the probability to detect the medium as idle and then that a packet is transmitted. When instead the channel is congested, a lower CCA sensitivity makes an ITS node to refrain from transmitting. Similarly, a higher data rate is advisable under high load, as it leads to a shorter packet air time.

Upon the arrival of a data packet at the MAC layer, the Transmit Queueing block reads the values of access priority, CCA threshold, transmit power and data rate, which have been preset in the packet header at the network layer. Based on the access priority value, this block inserts the packet in the appropriate transmit queue at the MAC layer – an event that should not occur at a rate greater than the reference value. The TRC mechanism is in charge of enforcing such requirement. Specifically, TRC delays a packet if necessary, and it may drop a packet if its transmission duration exceeds the maximum value corresponding to its access priority queue. Note that the latter is estimated thanks to the Transmit Statistics block.

Once a packet has been enqueued, the other values that have been preset at the network layer are compared by the DSC, the TPC and the TDC mechanisms against, respectively, the reference CCA sensitivity, the reference transmit power and the reference data rate. The preset values are lowered if they result to be above the reference values.

Finally, the TAC mechanism has been introduced with the aim of enforcing fairness among the transmit queues within a node as well as among different ITS nodes. In particular, the TAC defines the number of transmit queues that can be implemented. Furthermore, if the Transmit Statistics indicate that too many packets with a given priority index have been transmitted, the TAC “closes” the corresponding queue, which thus cannot send any more packets till it is reopened. In our work, we do not activate the TAC mechanism as it cannot be supported through the current standard MAC architecture.

III. SIMULATION SCENARIOS

In order to evaluate the DCC performance, we developed a new module in *ns*-2, which cooperates with 802.11 PHY and MAC modules. The implementation is fully compliant to the ETSI standard [1].

TABLE I
SIMULATION PARAMETERS

Layer	Parameter	Value
PHY	Frequency/Channel bandwidth	5.9 GHz/10 MHz
	Propagation	Nakagami (m=3)
	Power monitor threshold	-102 dBm
	Noise floor	-99 dBm
MAC	Slot time	13 μs
	SIFS	32 μs
	DIFS	58 μs
	Header length	40 μs
	aCWmin	15

TABLE II
DCC PARAMETERS

Parameter	Min	Default	Max
NDL_defDCCSensitivity	-	-85 dBm	-
NDL_ChannelLoad	0.2	-	0.5
NDL_refTxPower	-10 dBm	23 dBm	33 dBm
NDL_refPacketInterval	0.04 s	0.5 sec	2.0 sec
NDL_refDataRate	6 Mb/s	12 Mb/s	24 Mb/s
NDL_refCarrierSense	-95 dBm	-85 dBm	-65 dBm

As a reference topology, we use a 6×6 double-lane road *grid* in a $750\times750\,\mathrm{m}^2$-wide area. Roads are 150 m apart from each other, and vehicles are uniformly placed on the grid. Since we focus on the dynamics of the MAC protocol, we consider a snapshot of the topology where vehicles do not move; in this way, we can control exactly the number of neighbours as well as of interferers for each node. Vehicles are assumed to operate on the IEEE 802.11p SCH and to broadcast a packet each every 100 ms. Packets are tagged as belonging to the same access category at MAC Layer. The offered traffic load is a varying system parameter in our simulations, and it is varied by changing the data packet size.

In the environment outlined above, we consider two scenarios: in the former 600 vehicles are placed in the grid in Line-of-Sight (LOS) condition, whereas in the latter the signal attenuation due to buildings is taken into account through the Realistic Urban Grid (RUG) propagation model [6]. We will refer to such scenarios as LOS and Urban, respectively. Results obtained with a different number of vehicles have been obtained but they are omitted since they exhibited a similar behaviour. The main PHY and MAC-layer simulation parameters are set according to standard specifications and are summarised in Table I. Also, all the DCC parameters are set in accordance to the ETSI specifications [1], as reported Table II.

IV. PERFORMANCE EVALUATION

A. LOS Scenario

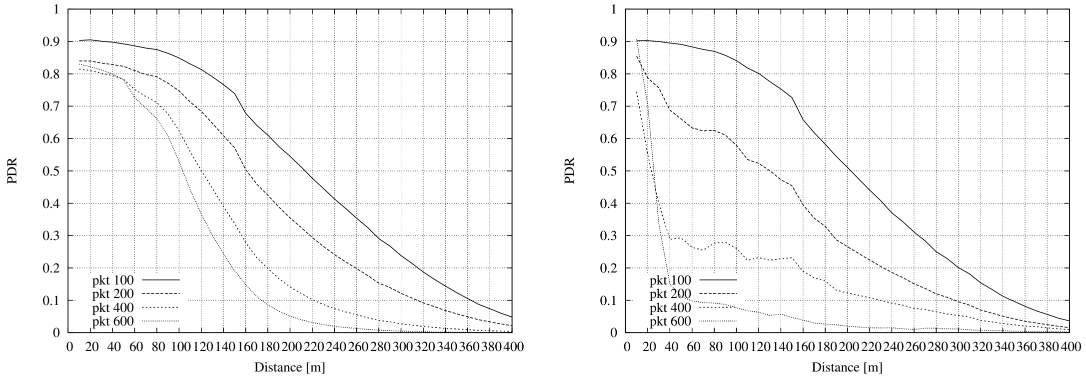
In the following, we show the impact that, separately, each of the DCC mechanisms has on the system performance, as well their joint effect when they are all triggered at the same time, both in the LOS and in the Urban scenarios. The legacy 802.11p CSMA/CA (labelled as “no DCC” in the plots and tables) is used as a benchmarking solution.

Fig. 1 shows the PDR as a function of the distance between communicating vehicles, and as the data packet size varies between 100 and 600 bytes. Recall that the packet generation rate is constant, thus a larger packet size implies a higher offered load; namely, as the packet size grows from 100 to 600 bytes, the offered load varies from 24% to 72%.

Looking at the plots, we can see that, as expectedx, the PDR decreases with the distance due to the greater attenuation, and it decreases as the packet size, i.e., the traffic load, increases. What it is surprising is the fact that, when separately activated, the single DCC mechanisms either bring a minor benefit in case of small packet size (TRC for 100 bytes and DSC for 200 bytes), no significative changes (e.g., TDC), or even a performance degradation (TPC for low-medium packet size, TRC for large packet size, and TDC). Overall, the joint effect of such mechanisms, depicted in Fig. 1(a), is a slight improvement and a small degradation, respectively, for short and long packets, with respect to the legacy 802.11p CSMA/CA scheme.

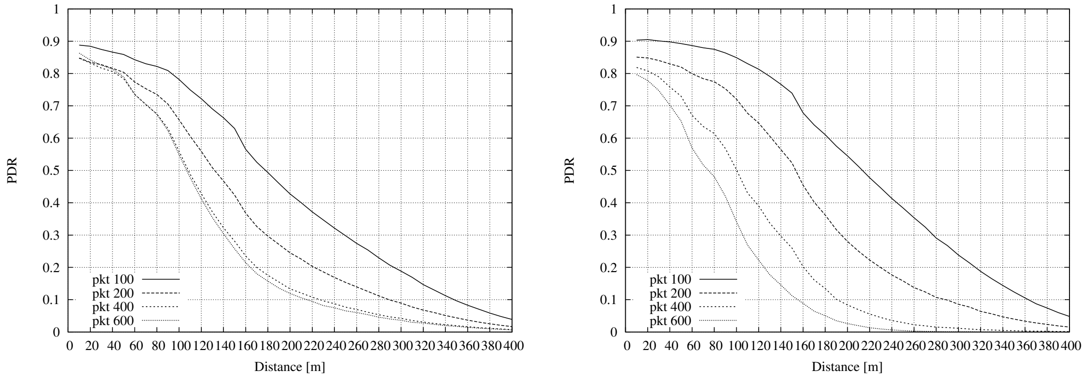
Table IV shows the packet access delay as a function of the packet size. The access delay is computed from the packet generation time instant at application layer, to its transmission on the channel. The delay increases with the packet size, as the increase in offered load leads to a higher collision probability. However, we notice a dramatic performance degradation when the full DCC scheme is enabled: the access delay increases from 504 μs under the legacy 802.11p CSMA/CA to 3.05 ms under the DCC. As shown by the values reported in the table, this behavior is mainly due to the TRC, which acts as a leaky bucket mechanism: it delays packets so as to maintain the reference packet interval. The other mechanisms, instead, slightly decrease the access delay. Indeed, the TPC reduces the power level as the channel load increases, thus making the channel appear as idle more often. As noted above, however, a lower power level degrades the PDR performance. The TDC increases the data rate, hence it reduces the packet air time and speeds up the transmission rate, although it leads to a higher error rate. Finally, as the channel load increases, the DSC lets the vehicles sense the channel with a higher carrier sense threshold of -65 dBm; it follows that the access delay decreases, at the cost of an increased collision probability (hence PDR).

Fig. 2 portrays the state taken by the nodes as a function of time, when either only the single mechanisms or the full DCC are activated. For brevity, only the results for 100 and 600 bytes are shown. Looking at the plots when TPC only is implemented, we note that this mechanism operates even under very low traffic load, as most of the nodes are in Active state for a packet size of 100 bytes. For a larger packet size, almost all nodes are in Restrictive state, suggesting that TPC alone is unable to keep the traffic congestion limited. A similar behaviour can be observed in the case of TDC and DSC. TRC, instead, is active in most cases and, even with 600-byte packet, it can reduce channel congestion, although at the price of a greatly increased delay. When all mechanisms are jointly implemented (full DCC), essentially the scheme behaves as TRC, which is therefore confirmed to be the dominant action. Another important observation, which holds



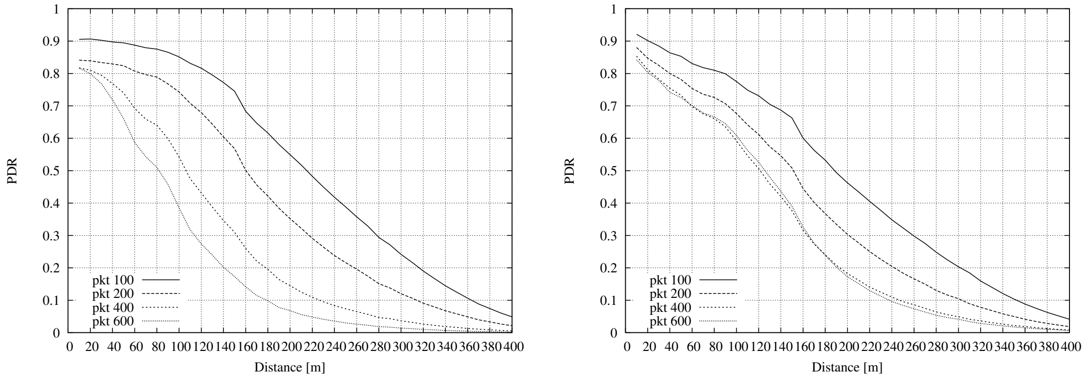
(a) no DCC

(b) TPC



(c) TRC

(d) TDC



(e) DSC

(f) full DCC

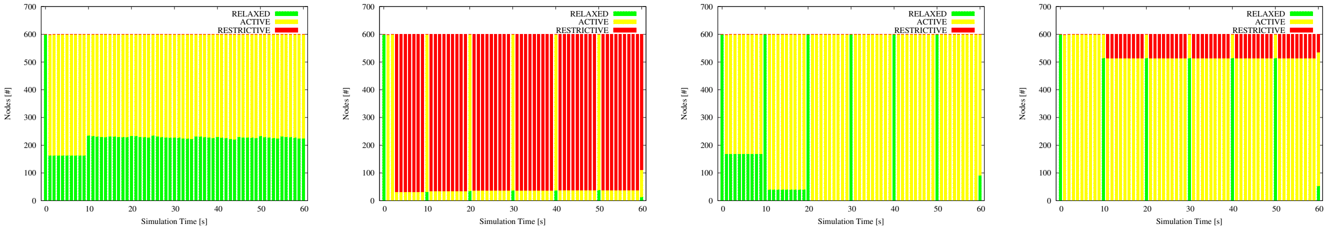
Fig. 1. PDR in LOS scenario as function of distance.

for all mechanisms, is that the node state exhibits an oscillatory behaviour, e.g., all nodes pass from active to relax and vice versa at the same time. This suggests that when the channel load, e.g., decreases, the DCC mechanism at all nodes reacts leading to an increased number, or duration, of transmissions. Then, upon observing a higher load, all nodes become less aggressive and the load decreases again. Such a behaviour is of scarce use and contributes to determining the poor performance of DCC.

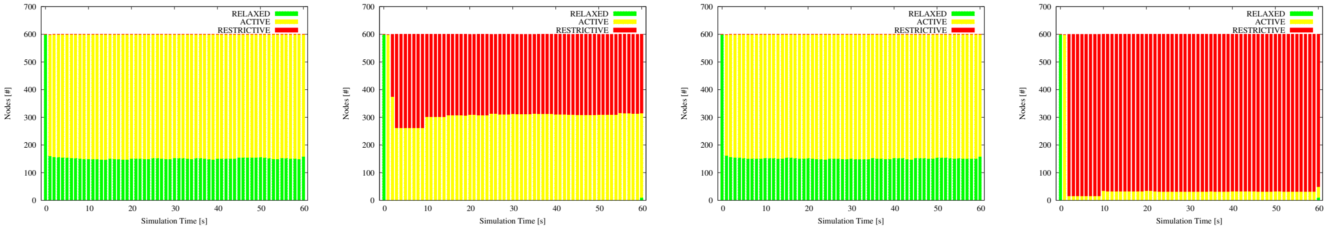
B. Urban Scenario

The PDR versus the receiver distance in the Urban scenario is depicted in Fig. 3, for different values of the packet size. The comparison between the case where DCC is not implemented and the full DCC highlights that the same performance is achieved in both cases. This is due to the fact that in the Urban scenario the attenuation introduced by the buildings greatly limits the signal propagation, thus reducing the number of vehicles interfering with each other. It follows that the channel load is always below the minimum threshold and the DCC is rarely active.

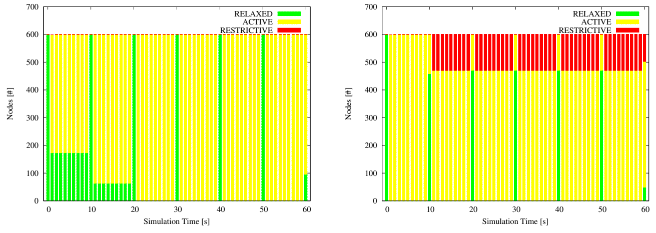
The only mechanism that is triggered for a significant amount of time is the TRC when the packet size is 600 bytes, as confirmed by the values of access delay reported in Table III. Interestingly, the delay obtained through DCC for 600-byte packets is much greater than with the legacy 802.11p. This suggests that TRC becomes active unnecessarily, i.e., it delays packets at the MAC layer even if a higher traffic load



(a) TPC: Packet size 100 Byte. (b) TPC: Packet size 600 Byte. (c) TRC: Packet size 100 Byte. (d) TRC: Packet size 600 Byte.



(e) TDC: Packet size 100 Byte. (f) TDC: Packet size 600 Byte. (g) DSC: Packet size 100 Byte. (h) DSC: Packet size 600 Byte.



(i) full DCC: Packet size 100 Byte. (j) full DCC: Packet size 600 Byte.

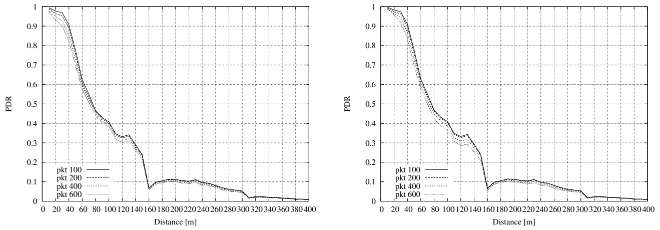
Fig. 2. Histogram of the operational states with the TPC (a,b), TRC (c,d), TDC (e,f), DSC (g,h) mechanisms and full DCC (i,j), as function of time, in the LOS scenario.

could be supported on the channel.

Fig. 4 further clarifies the system behaviour when the packet size is set to 600 bytes. The plots present the state taken by the TPC and the TRC as a function of the vehicle distance from the nearest intersection (as farther than that the signal propagation is blocked by the presence of buildings). The histograms for the TDC, the DSC and the full DCC have been omitted, as the first two mechanisms exhibit the same behaviour as in the case of TPC, while the plot for the full DCC is the same as for the TRC. The results clearly highlight that most of the time vehicles are in Active state with TRC, while they operate in Relaxed state with the other mechanism, hence, as remarked above, the DCC performance is determined by the TRC only.

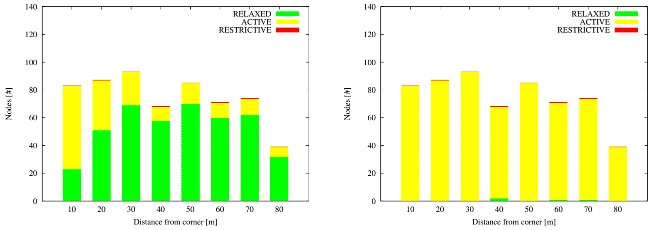
V. CONCLUSIONS

We investigated through extensive simulations the performance of the DCC scheme, as currently specified by ETSI. In particular, we studied the impact of each of the DCC mechanisms on the system performance, as well their joint effect when they are all triggered at the same time. The analysis has been carried out in a vehicular scenario where nodes are in radio visibility as well as in a urban scenario accounting for the presence of buildings. In both cases, our results highlight that DCC has little effect. Furthermore, the DCC behaviour is mainly determined by the transmission rate control mechanism, which may even degrade the system performance with respect to the case where the legacy 802.11p MAC protocol is implemented. Our future works will certainly investigate the upcoming DCC solution but also variations in the settings of current DCC, slightly different algorithms [7] and different non-local channel measurements as proposed in [4].



(a) No DCC (b) full DCC

Fig. 3. PDR in Urban scenario as a function of distance.



(a) TPC (b) TRC

Fig. 4. Histogram of the operational states with TPC and TRC as functions of the minimum distance from the nearest intersection, in the Urban scenario and with packet size of 600 bytes.

TABLE III

PACKET ACCESS DELAY IN THE URBAN SCENARIO

Packet Size [byte]	No DCC [s]	TPC [s]	TRC [s]	TDC [s]	DSC [s]	Full DCC [s]
100	0.000054	0.000054	0.000121	0.000054	0.000059	0.000126
200	0.000070	0.000070	0.000137	0.000070	0.000078	0.000145
400	0.000110	0.000110	0.001880	0.000110	0.000128	0.001790
600	0.000168	0.000167	7.21	0.000168	0.000186	7.85

TABLE IV

PACKET ACCESS DELAY IN THE LOS SCENARIO

Packet Size [byte]	No DCC [s]	TPC [s]	TRC [s]	TDC [s]	DSC [s]	Full DCC [s]
100	0.000504	0.000482	15.31	0.000504	0.000594	14.98
200	0.000809	0.000508	19.14	0.000769	0.000783	15.55
400	0.001510	0.000404	19.99	0.001090	0.000850	20.57
600	0.003050	0.000427	19.97	0.001440	0.001070	20.50

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