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Evaluation of C-V2X Sidelink for Cooperative Lane Merging in a Cross-Border Highway Scenario

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Abstract—In this paper, we explore the potential, as well as a few limitations, of Cellular - Vehicle-to-Everything (C-V2X) sidelink connectivity (a.k.a., PC5-Mode4) for Cooperative Lane Merging (CLM) services in a specific cross-border highway context. Based on a dedicated simulation flow, we assess both the successful completion of the CLM negotiation procedure from the standpoint of messages delivery (service availability) and the accuracy of position awareness, as perceived by the manoeuvre management application out of collected status messages (service reliability). These indicators are evaluated as a function of road traffic, overall system latency and infrastructure deployment. Simulation results suggest that both Vehicle-to-Infrastructure and Vehicle-to-Vehicle communications based on C-V2X PC5-Mode4, which benefit respectively from information redundancy and short-range links, could advantageously complement Vehicle-to-Network connectivity to locally guarantee the seamless continuity of latency-critical services in challenging environments.

I. INTRODUCTION

The fifth generation (5G) of wireless communications is expected to support Vehicle-to-Everything (V2X) connectivity in a variety of Cooperative Intelligent Transport Systems (C-ITS) and road services related to safety, energy efficiency or infotainment, even at low levels of automation (i.e., cooperative manoeuvring, situation awareness, video streaming, green driving [1]). In this regard, canonical scenarios and high level radio requirements have been provided in [2] for the evaluation of V2X use cases based on the 4G Long Term Evolution (LTE) and 5th Generation - New Radio (5G-NR). V2X connectivity is generally meant to comprise Vehicle-to-Network (V2N) links with respect to Base Stations (BSs), Vehicle-to-Infrastructure (V2I) links with respect to Road Side Units (RSUs), and Vehicle-to-Vehicle (V2V) links. Depending on the operating conditions, one can thus rely on timely combinations of these V2V, V2I and V2N means.

In this context, the socio-economic necessity to develop large continental road corridors (e.g., along the 600km-long highway between Bologna and Munich, over three European countries) raises a variety of challenges that have been rarely addressed in the literature so far. Major stakes typically concern seamless cross-border service continuity, overall network architecture, radio technology, and infrastructure deployment [3]. In such cross-border situations, today's V2N-based cellular approaches may not fulfil all the requirements of most demanding services, in terms of availability, reliability and latency (e.g., due to time-consuming network re-selection), thus calling for complementary or even alternative connectivity mechanisms and architectures (incl. both centralized and

decentralized shorter-range solutions). This is all the more critical since cross-border environments are usually complex and thus, more prone to generating accidents, due to mixed road traffic densities, specific road topology, heterogeneous country-wise driving policies... Beyond, cross-border operations also raise questions regarding the chain of added values and costs in a multi-tenant ecosystem (incl. road operators, mobile network operators, cars and equipment manufacturers, service providers, institutional entities...). Both technical and non-technical issues are currently investigated in the 5G-CARMEN project [4].

In this paper, we explore the potential of V2V/V2I connectivity based on Cellular - V2X (C-V2X) sidelink (a.k.a., PC5-Mode4) in a specific cross-border highway context, while considering a Cooperative Lane Merging (CLM) use case that mainly relies on cooperative position awareness. It is indeed essential to determine if and how PC5-Mode4 V2V/V2I, in such environments, could plausibly complement V2N connectivity, in case the latter would suffer from coverage shortage and/or prohibitive latency. Both connectivity and application Key Performance Indicators (KPIs) are herein evaluated through simulations, accounting respectively for the successful reception of all the critical messages exchanged during the CLM negotiation phase on the one hand (thus, assessing service availability), and for the uncertainty of the location information used to make CLM decisions at the application level on the other hand (thus, assessing service reliability). For this scenario, we consider a decentralized mode based on direct V2V transactions and a semi-centralized mode based on V2I links with respect to RSUs, both with PC5-Mode4. The evaluation is carried out as a function of road traffic density and overall CLM negotiation duration (i.e., beyond radio access latency), under various infrastructure deployment assumptions. Another paper contribution lies in the proposed simulation-based evaluation framework and methodology to assess system-level KPIs, given a particular message sequence and an imposed connectivity architecture.

II. USE CASE AND WORKING ASSUMPTIONS

A. Cooperative Lane Merging Use Case

CLM has been selected as a flagship use case to pilot through field trials in [5]. Beyond specific implementation settings, critical aspects of this use case can be more easily assessed and illustrated by means of simulations (e.g., pointing out dependencies between connectivity performance and

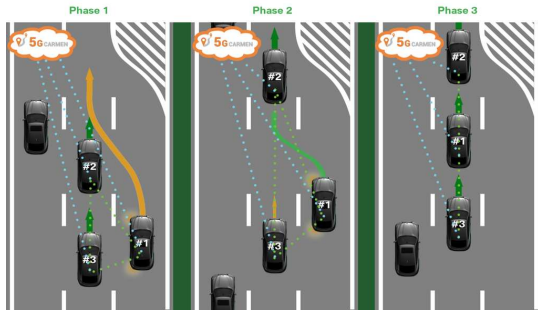


Fig. 1: Illustration of a 3-phase V2X-assisted CLM use case [1].

position awareness quality, exploring a wider range of both traffic and infrastructure densities...).

In a typical CLM, as illustrated in Fig. 1 [1], one vehicle intends to insert onto a side lane where other vehicles are already driving (e.g., due to the presence ahead of an accident, a static vehicle, a working area...). Depending on their respective positions, the side vehicles shall hence create a gap, for instance by slowing down or speeding up, to allow the initiator to insert. This manoeuvre is based on the prior exchange of positional information between the different parties (see Sec. II-C). In a cross-border highway context, this CLM procedure can be initiated and completed before, while or after crossing the border. The period between the request and the actual lane merge event is hereafter referred to as *CLM negotiation phase*.

B. Simplified Architecture and Related Deployment Aspects

To support the CLM negotiation, two simplified system architectures have been considered in our study (see Fig. 2). In a first semi-centralized mode, we assume V2I connectivity via PC5-Mode4 with respect to RSUs (i.e., making a distinction with a pure centralized V2N-based mode wrt. cellular BSs). These RSUs are assumed to be connected via fiber to a centralized computation-storage resource hosting the manoeuvre management application (e.g., Mobile Edge Cloud (MEC) or a simple server). In the second decentralized mode, we consider V2V connectivity via PC5-Mode4, along with on-board applications.

In the semi-centralized RSU-assisted mode, all the RSUs deployed around the border are expected to collect (resp. send) information from (resp. to) the common centralized resource in charge of elaborating a “bird’s eye view” (i.e., to the best of all collected position awareness messages) and making CLM decisions accordingly. A RSU close enough from the border in one country is expected to be still exploitable by vehicles under its coverage in the other country right after crossing the border, thus contributing to cross-border service continuity. Beyond, several RSUs deployed on both sides of the border (i.e., by two distinct road operators) could also contribute to a common bird’s eye view, while relying either on a shared/unique centralized resource or on distinct coordinated centralized resources, given low-latency cross-border connections between them.

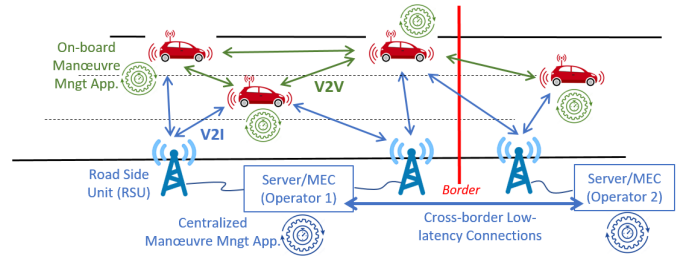


Fig. 2: Simplified deployment and architecture considered in semi-centralized (blue) or decentralized (green) CLM.

C. Messages Sequence

For the CLM negotiation, two preliminary messages sequences were defined in [1], depending on the considered decentralized or (semi-)centralized configuration. In Fig. 3, due to paper length limitation, we show uniquely the messages sequence chart corresponding to the (semi-)centralized option. Accordingly, default *status* update messages are continuously broadcast by the vehicles, including that involved in the CLM. These messages are collected by the RSUs and further forwarded to the MEC/server in charge of running the manoeuvre management application. At the beginning of the negotiation phase, the initiator sends a *request-to-merge* message, which is similarly captured by the infrastructure and forwarded to the application. In return, based on the analysis of the latest received *status* update messages (and thus, based on the relative positions claimed by involved vehicles), the application issues both *recommendation* message(s) to the vehicle(s) that are expected to create the gap to facilitate the initiator’s insertion, as well as a *safe-to-merge* (or *merge denial*) message back to the initiator, via the RSUs.

III. EVALUATION FRAMEWORK AND METHODOLOGY

A. Overall Simulation Flow

A system-level simulation flow inheriting from [6] has been expanded to evaluate these CLM negotiations. Accordingly, mobility traces (incl. time-stamped vehicles’ 2D coordinates, 2D speed and absolute heading) are first generated offline using the Simulation of Urban MObility (SUMO) tool [7], based on real traffic data under various road densities. Out of the previous traces, “natural” lane merging events involving subsets of 3 vehicles have been detected in the simulated flow via post-processing in Matlab®. The mobility traces then feed the generation of time-stamped connectivity traces via ns-3, accounting for the successful/failed reception of all requested CLM negotiation messages, as well as time-stamped sensor data traces based on simplified Matlab models (e.g., erroneous Global Positioning System (GPS) Real Time Kinematics (RTK) data in our case). Finally, the previous mobility, connectivity, and sensor data traces are all post-processed in Matlab to assess both connectivity and application KPIs for the detected lane merge events. Mobility and connectivity simulations are deliberately decoupled since we perform an information-centric evaluation of V2X connectivity during the CLM negotiation (prior to execution), hence requiring no controlled feedback onto real-time vehicles mobility.

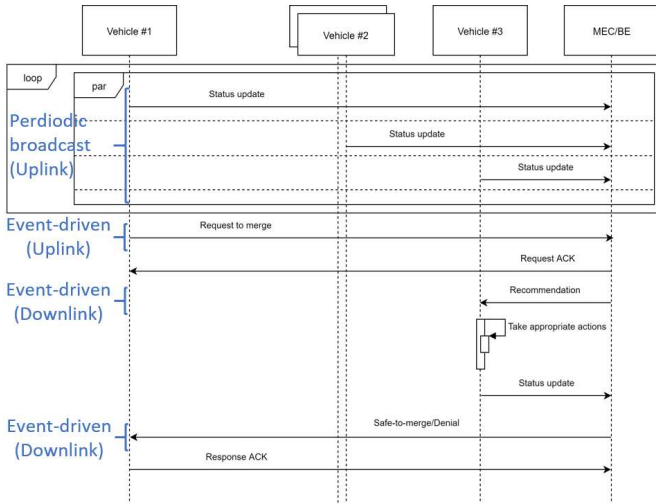


Fig. 3: Messages sequence in the V2I-based semi-centralized CLM mode [1].

B. Environment Description and Road Traffic Parameters

The environment of interest is composed of a 4.5 km-long portion of the A22 highway located at the border between Italy and Austria, along with its secondary roads (e.g., the service lane SS12). This portion of highway comprises a 800m-long tunnel, where we assume the presence of GPS repeaters to deliver the timing reference to both V2V and V2I.

Based on real traffic measurement data collected in 2019 at the Italian-Austrian border by Autostrada del Brennero, we have derived macroscopic mobility parameters to configure our SUMO simulations. These measurements reveal an upper (resp. lower) limit on the traffic flow in each driving direction at approximately 2500 (resp. 750) vehicles per hour over the most busy working hours (i.e., 9.00am-6.00pm). This corresponds to an average traffic density of 83 (resp. 28) vehicles per kilometer. Finally, 90% of the simulated vehicles were assumed to drive along the A22, without taking any service lane (i.e., staying in the A22 main loop). Based on the previous traffic and mobility configuration, up to 90 “natural” lane merging situations involving 3 vehicles could hence be detected under the highest traffic density, out of 3 minutes of a free-running SUMO simulation (i.e., 30/min).

C. Infrastructure Deployment

We have considered increasing artificially the number of units to evaluate the impact of road infrastructure. This density varies from 0.5 RSUs/km (i.e., 2 RSUs over 4.5km, in line with the current real-life field deployment) to 2 RSUs/km (i.e., 8 RSUs over 4.5km), thus quadrupling the baseline density.

Following an abstract and agnostic approach, simulation results are expressed as a function of the overall CLM negotiation duration, which is viewed here as an input parameter. The latter thus includes the extra latency induced by higher layers/segments of the connectivity architecture (i.e., transport, core and orchestration durations, computation time...), beyond radio access latency (i.e., beyond vehicle to RSU latency). This deliberately simplified representation could be helpful to map

a posteriori more concrete latency figures onto both RSUs and MEC/server deployment assumptions in future studies.

D. Radio Parameters

The main parameters considered at the radio physical (PHY) layer level for the simulation of PC5-Mode4 are summarized in Table I, assuming no packet segmentation but integral transmissions within time frames of 1 ms, as in [8]. Regarding path loss, we have considered an empirical 2-slope log-distance average attenuation model (in dB) with normal shadowing. The model parameters, which are conditioned upon the Line of Sight (LoS) or Obstructed Line of Sight (OLoS) channel status (assuming OLoS when at least one vehicle is obstructing the link), have been calibrated based on real field measurements [9].

TABLE I: Radio PHY parameters considered in PC5-Mode4 simulations

Central frequency	5.9 GHz
Transmit power	23 dBm
Selection window	100 TTIs
Reselection probability	1
Nb. of RBs per Resource	50
Messages size (status/others)	200/125 bytes
Nb. of RBs for the TBs	36
Modulation and coding scheme	3/0
2-slope path loss exponents in LoS/OLoS	{-1.81,-2.85}/{-1.93,-2.74}
2-slope path loss breakpoint distance	100 m
Reference path loss at 10 m in LoS/OLoS	-63.9/-72.3 dB
Shadowing std. in LoS/OLoS	4.15/6.67 dB

The PC5-Mode4 Medium Access Control (MAC) layer is based on a Sensing-Based Semi-Persistent Scheduling (SB-SPS) algorithm, for which we have considered a selection window of 100 ms. Knowing the Transmission Time Interval (TTI) occupancy of each single node, the Signal to Noise and Interference Ratio (SINR) per simulated link and accordingly, the average Packet Error Rate (PER), can thus be computed as a function of simulation time [10] (e.g., PHY PER performance vs. SINR can be derived from [8]). Accordingly, random realizations of packet reception/loss are drawn for each transmission attempt in the CLM messages sequence. Retransmissions at the PHY level are not permitted for simplicity.

E. Messages Formats and Rates

Packet sizes of 125 bytes are assumed for on-demand *request-to-merge*, *notification* and *safe-to-merge/denial* messages. The communication from the application to the vehicles is based on Decentralized Environmental Notification Messages (DENMs) whereas *status* update messages of 200 bytes, which encapsulate local GPS RTK data, are based on standard Cooperative Awareness Messages (CAMs).

Beside the few vehicles involved in the local CLM procedures under test, all the other vehicles belonging to the simulated flow are assumed to broadcast their own messages at the same nominal average rate of 10Hz under Decentralized Congestion Control (DCC). In the low traffic scenario, the analysis of the Channel Busy Ratio (CBR) indicator shows that DCC is never activated, whereas in the high traffic scenario, the transmission rate is regularly reduced down to 2 Hz.

Beyond, channel congestion could anyway be limited in case of drastic speed reduction, as CAM rate is scaled down [10].

F. Position Awareness Errors, Drifts and Corrections

Errors affecting perceived vehicles' locations when decisions must be made are impacted by two cumulative effects. First, GPS position estimates are erroneous depending on the type/class and operating conditions of on-board receivers. Then, position awareness information can be outdated, due to the overall time elapsed between GPS estimation and decision making under vehicles mobility. This phenomenon can result from the loss or postponing of intermediary status messages and/or from possibly large extra latency delays induced in semi-centralized CLM modes. To mitigate the latter sources of error, using both the estimated speed vector (conveyed in status messages) and the known time elapsed till decision, the application is assumed to make linear mobility-based predictions to "re-synchronize" position information (e.g., based on a priori Gauss-Markov models [11], [12]).

G. Performance Indicators

On the one hand, as regards to service availability (i.e., from the connectivity perspective), we evaluate the capability to correctly receive all the messages requested in the negotiation phase, till the moment vehicles take actions. Concretely, in the absence of re-transmissions, a semi-centralized negotiation is thus declared successful if the request message from the initiator vehicle is received by at least one of the RSUs, the recommendation is received by the second vehicle in charge of creating the gap and the safe-to-merge (or denial) message from the infrastructure is received by the initiator. This indicator is thus strictly bounded to single link reliability. On the other hand, as regards to service reliability (i.e., from an automotive application perspective), we also evaluate the quality of position/speed awareness information feeding the CLM manoeuvre management application after mobility-based prediction, when the service is available (i.e., given that all messages are correctly received). From this application standpoint, the CLM negotiation is thus declared successful if the accuracy of perceived location information jointly falls within an a priori tolerance threshold for the three involved vehicles. This threshold is set in our case from 1 m (as the minimum accuracy to determine lane occupancy) down to 0.1 m (e.g., for finer in-lane trajectory control). For the two KPIs, statistics are drawn over the total number of detected lane merging events, as well as over multiple random radio trials for each single lane merging event (typically, in terms of noise realizations, random access to the medium, etc.) to ensure sufficient diversity over both road traffic and radio dimensions.

IV. RESULTS AND DISCUSSIONS

A. Semi-Centralized CLM Negotiation over V2I Connectivity

We first consider a semi-centralized V2I-based CLM negotiation under moderate traffic density (28 veh./km), while varying the road infrastructure density. Fig. 4 (Bottom) shows the corresponding success/failure rates as a function of CLM

negotiation duration for 0.5 RSU/km (a), 1 RSU/km (b) and 2 RSUs/km (c). Note that a reference (i.e., theoretical) zero-latency scenario is also evaluated here for benchmark purposes. It is then observed that the amount of CLM rejections due to connectivity is relatively low under such moderate traffic conditions, even in case of baseline road infrastructure density (typically, with a median rejection rate of 2.5% over the tested configurations). Overall, most of the CLM rejections would be due to unsatisfied localization requirements. Despite the applied mobility-based compensation mechanism, position awareness information indeed gets more and more outdated as end-to-end latency increases (i.e., vehicles have travelled a significant distance between the moment when GPS RTK has produced its reading and the moment when the application must make its decision, making the prediction not sufficiently reliable). As expected, the addition of extra RSUs (i.e., doubling the initial road infrastructure density) contributes to improve further the CLM success rate according to the connectivity criterion, with a median failure rate of 1.3% (resp. 0%), as soon as a density of about 1 RSU/km (resp. 2 RSUs/km) is reached. The latter observation does not necessarily mean that all the intermediary messages are successfully received but, benefiting from information redundancy, one adjacent RSU could back another unit experiencing poorer connectivity so as to complete the "bird's eye view". Besides, as also expected, under higher RSUs density, the global trend with respect to the CLM negotiation duration remains approximately the same as previously. All in all, under low traffic density, the extra latency is clearly the dominating limiting factor, impacting mainly the quality of position awareness at the application level, whereas even quite sparse deployment of PC5-Mode4 enabled RSUs would already ensure quite high cross-border service continuity in terms of connectivity, given that at least one RSU is close enough from the border.

Fig. 4 (top) shows similar results under high traffic conditions, when all other vehicles broadcast their packets. In this case, even if DCC contributes to reduce the probability of message collisions, as expected, the connectivity performance is now significantly degraded when compared to the initial low traffic scenario, with a median rejection rate of approximately 27.8% for the baseline infrastructure density. However, performance levels comparable to that of low traffic conditions can be restored with a median rejection of 6.1% (resp. 0.5%) according to the connectivity criterion, as soon as the road infrastructure reaches 1 RSU/km (resp. 2 RSUs/km).

B. Decentralized CLM Negotiation over V2V Connectivity

Fig. 4 (d) also shows the results of a decentralized V2V-based CLM negotiation relying on PC5-Mode4. Here, the CLM negotiation duration mostly comprises the computation time when running the application aboard vehicles. Hence, performance is not evaluated beyond durations of 20 ms.

In comparison with semi-centralized schemes under sufficiently densified deployment, we thus observe only little performance degradation according to the connectivity criterion, with a median rejection rate of 4.0% (resp. 4.5%)

V. CONCLUSIONS

Based on system simulations, we have assessed the performance of a canonical CLM case based on PC5-Mode4 V2V/V2I connectivity in a specific cross-border highway scenario. Despite rather pessimistic assumptions in terms of road traffic density and technology penetration (i.e., all the vehicles in the simulated high-traffic flow are assumed to broadcast messages), both RSU-assisted semi-centralized and decentralized CLM modes based on PC5-Mode4 seem to provide reasonably high levels of service availability from a pure connectivity standpoint, while benefiting respectively from information redundancy/diversity (i.e., from multiple RSUs) and short-range communication links. Obviously, the cross-border nature of the chosen environment has only limited impact onto this preliminary V2V/V2I performance evaluation (apart from real in-site road traffic conditions and the presence of a tunnel section). However, the observations above suggest that V2N could be advantageously combined with PC5-Mode4 V2V/V2I links in case of local coverage shortage.

Future works will consider (i) evaluating the performance of centralized CLM negotiation over V2N 5G-NR connectivity in the same cross-border environment, (ii) combining centralized and decentralized modes in a variety of inheriting sub-scenarios (incl. in-lane transactions), (iii) assessing heterogeneous data/messages traffic (i.e., at various rates and formats), and (iv) deriving refined latency budgets (e.g., based on [13]).

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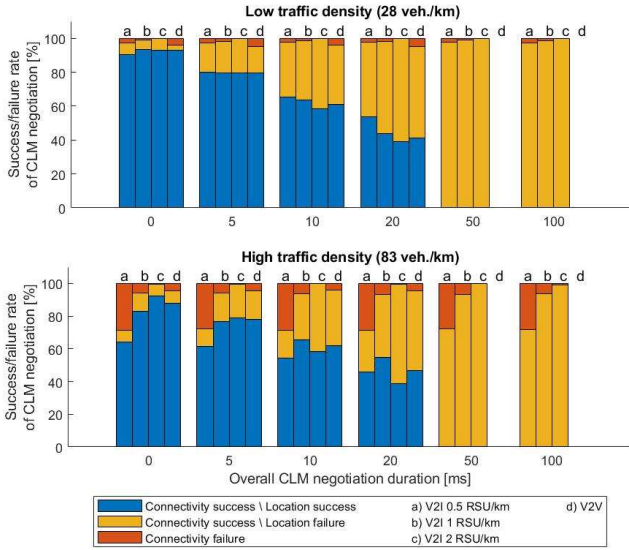


Fig. 4: Success/failure rate of semi-centralized (resp. decentralized) CLM negotiation based on V2I (resp. V2V) PC5-Mode4 under high traffic density (Top - 83 veh./km) and low traffic density (Bottom - 28 veh./km), while other vehicles broadcast packets at the nominal rate of 10Hz with DCC on and assuming a 1-m tolerance threshold for the localization criterion.

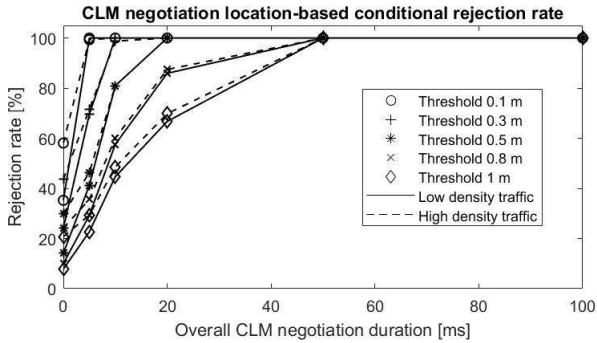


Fig. 5: Rejection rate of CLM negotiation according to the location-oriented criterion only, as a function of location tolerance threshold, given that the connectivity criterion is successfully met.

under low (resp. high) traffic density. Provided a sufficient road infrastructure density, RSU-assisted CLM somehow benefits from information redundancy, thus increasing the overall probability of packet reception (e.g. assuming that 2 RSUs can receive/send the same messages). Dually, V2V-based schemes rely on single communication links at much shorter ranges, hence benefiting from more favorable propagation conditions.

Finally, Fig. 5 focuses on the rejection rate according to the localization criterion for different values of the location tolerance threshold, as a function of the CLM negotiation duration, given that all the required packets are successfully received. One can see how CLM service reliability can rapidly and dramatically deteriorate as the negotiation duration increases, hence emphasizing again the importance of ultra low latency end-to-end V2X transactions to enable demanding levels of automation. More marginally, one can also note the collateral effects of systematically activating DCC under high traffic conditions, as decreasing the broadcast rate of *status* update messages imposes the use of more outdated information.