Evolution of Vehicular Congestion Control Without Degrading Legacy Vehicle Performance

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***Abstract*—Channel congestion is one of the major challenges for IEEE 802.11p-based vehicular ad hoc networks. To tackle the challenge, several algorithms have been proposed and some of them are being considered for standardization. Situations could arise where vehicles with different algorithms operate in the same network. Our previous work has investigated the performance of a mixed-algorithm vehicular network for the CAM-DCC and LIMERIC algorithms and identified that the CAM-DCC vehicles could potentially experience a performance degradation after introducing the LIMERIC vehicles into the network. In this work, we study whether it is possible to eliminate or bound this degradation. We propose a CBP target adjustment mechanism which controls the CBP target of LIMERIC vehicles according to vehicle density and mixing situation of the two algorithms in the network to limit the performance degradation of CAM-DCC vehicles to a desired level. The proposed mechanism is evaluated via both MATLAB and ns-2 simulations and the simulation results indicate that the performance degradation of the CAM-DCC vehicles is controlled as expected with only negligible impact on the performance of LIMERIC vehicles, which still perform similar or better than CAM-DCC vehicles.**

I. INTRODUCTION

To enable Intelligent Transportation System (ITS) applications, especially safety applications, each vehicle has to frequently exchange safety messages including its vehicle state (e.g., position, heading and speed) with other neighboring vehicles via vehicle-to-vehicle communications (V2V). These safety messages are referred to as Cooperative Awareness Messages (CAMs) in Europe [1] and Basic Safety Messages (BSMs) in the U.S. [2]. Once the number of V2V equipped vehicles is large, congestion can arise on the wireless channel, which leads to dropped or delayed safety messages, and affects the reliability of ITS applications. Several algorithms have been proposed to control the congestion, reduce packet error rate and improve the reliability of safety applications [3]–[6]. A recent European Telecommunication Standards Institute (ETSI) standard, ETSI TS 103 175, V1.1.1 [7], presents two algorithms that can satisfy decentralized congestion control (DCC) requirements, one state-based reactive approach, which we refer to as CAM-DCC [8] for consistency with earlier literature since it is the original CAM-DCC algorithm, and one linear adaptive approach, which is based on the Linear MEssage Rate Integrated Control (LIMERIC) [9] algorithm. We refer to the linear-adaptive control in the CAM-DCC framework as LIMERIC.

At a future point, one may expect that the system will need to transition to improved versions of congestion control algorithms. Such considerations can already be found in the final report of the C-ITS Deployment Platform [10]. While the CAM-DCC algorithm is recommended for day one deployment, the report also implies that more sophisticated DCC solutions for more demanding applications should be realized in the future. Due to its better performance in convergence, fairness and stability, LIMERIC is considered as one of such sophisticated DCC solutions for future deployment.

Hence, due to such system evolution issues, a situation could arise where vehicles with two different algorithms operate in the same network, a situation that we refer to as mixed networks. In our previous work [11], we have conducted a case study of a mixed network with the CAM-DCC algorithm and the LIMERIC algorithm via ns-2 simulations, and we observed in the given scenario that, while the performance change is relatively small (less than 10% in term of packet error rate), the performance of CAM-DCC vehicles can be degraded in the mixed network compared to an all CAM-DCC network. This raises the question whether such performance degradation can be limited, if not eliminated.

In this work, we, therefore, propose a CBP[1] target adjustment mechanism for LIMERIC which controls the performance degradation of existing CAM-DCC vehicles to a desired level. The main idea is to adjust the CBP target of LIMERIC vehicles according to vehicle density and mixing situation in a network such that LIMERIC vehicles spare enough channel capacity for CAM-DCC vehicles to transmit as in an all CAM-DCC network. The proposed mechanism estimates at which CAM-DCC state the CAM-DCC vehicles are desired to operate in the mixed network and then adjust the CBP target in a way such that the steady-state CBP of the network is within the CBP range associated with that state.

We evaluate the proposed mechanism in mixed networks with a variety of vehicle densities and mixing situations via MATLAB and ns-2 simulations. For MATLAB simulations, the node density varies from 100 to 1000 while the mixing ratio of LIMERIC nodes changes from 0% to 100%. For ns-2 simulations, a highway scenario is simulated with 250 and 500 vehicles, varying the LIMERIC's mixing ratio from 20% to 80%. Extensive simulation results show that with the target adjustment, the performance of CAM-DCC vehicles in mixed networks is able to preserve while the performance of LIMERIC vehicles is better or similar. The main contributions of this paper can be summarized as follows:

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[1] CBP, Channel Busy Percentage, is defined as the fraction of time during which the channel is measured as busy and it serves as an indicator of the channel condition

- A mechanism is proposed to adjust the CBP target of LIMERIC vehicles, resulting in changes in measured CBP, such that the degradation of CAM-DCC vehicles is controlled to a desired level.
- As evaluated via MATLAB and ns-2 simulations with a variety of vehicle density and mixing situation, the proposed mechanism is able to decrease the degradation in terms of inter-packet gap to less than 1.4%.
- While preserving the performance of CAM-DCC vehicles, LIMERIC vehicles can outperform CAM-DCC vehicles up to 20% in terms of inter-packet gap.

II. MIXED NETWORKS

Inspired by the ETSI standardization considerations [7], we study a scenario where the original state-based CAM-DCC algorithm is deployed initially and then vehicles with the original LIMERIC algorithm plus CAM message generation are introduced at a later time. At least for a transition phase, it is possible that vehicles with different algorithms could mix on a road and form what we refer to as a mixed network.

As defined in current standards, both algorithms serve as gatekeepers to regulate the CAM message generation process [1]. In essence, a vehicle generates CAMs based on its kinetic status, i.e., changes in its position, speed or heading. The maximum rate at which those messages are sent is then limited by the congestion control algorithms. Both algorithms use CBP measurements as algorithm input. However, the two algorithms differ in fundamental design philosophy. The CAM-DCC algorithm maps a measured CBP to a transmission rate through a predefined look-up table. LIMERIC instead implements an adaptive controller to drive CBP towards a target that maximizes the network throughput.

A. State-based control (CAM-DCC)

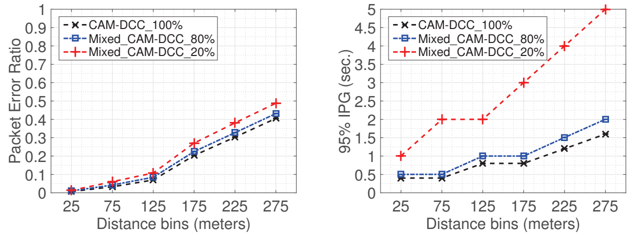
As a state-based reactive approach, the CAM-DCC algorithm defines a RELAXED, multiple ACTIVE and a RESTRICTIVE state. Each state associates a certain range of CBP values with a packet transmission rate. Through a table look-up, a CAM-DCC vehicle uses the transmission rate whose associated CBP range includes the measured CBP. Table I presents the states defined in [7] and used in our simulations.

TABLE I: CAM-DCC look-up table

State Index	Channel Load	State	Packet Tx Interval	Packet Tx Rate
4	**<30%**	RELAXED	100 ms	10 Hz
3	**30-39%**	ACTIVE 1	200 ms	5 Hz
2	**40-49%**	ACTIVE 2	400 ms	2.5 Hz
1	**50-59%**	ACTIVE 3	500 ms	2 Hz
0	**$\geq$ 60**	RESTRICTED	1000 ms	1 Hz

B. Linear adaptive control (LIMERIC)

LIMERIC is a linear adaptive algorithm that adjusts vehicles' transmission rate in a way such that the channel load is driven to a predefined target. The target is typically high (e.g. $> 60\%$) for higher throughput. More details of the algorithm can be found in [9]. In order to ensure vehicles which contribute to congestion at a given location participate in congestion control in a fair manner, the PULSAR [12] information dissemination functionality has been added. PULSAR requires each vehicle shares its local measured CBP and the maximum CBP reported by its one-hop neighbors in safety messages, such that each vehicle can acquire CBP information over a two-hop range. Reacting to the same maximum CBP over a two-hop range, LIMERIC vehicles can control the congestion fairly.



(a) (b)

Fig. 1: PER and 95th percentile IPG for a mixed network with 500 vehicles

C. Mixed network performance degradation

Our previous work has identified that introducing LIMERIC vehicles to the network can potentially let CAM-DCC vehicles experience a certain level of performance degradation in terms of packet error ratio (PER) and inter-packet gap (IPG).[2] Fig. 1 presents the PER and the 95th percentile IPG results of a scenario where 500 vehicles are moving on a highway. More details of the scenario setting are described in Section IV. The results are organized in distance bins according to the distance between the transmitter and the receiver. Fig. 1a shows that the PER of CAM-DCC vehicles increases by 5-10% as the percentage of LIMERIC vehicles in the network (the LIMERIC mixing ratio) rises from zero to 80%. A similar trend is also observed in Fig. 1b. The IPG value at the first distance bin of the CAM-DCC 100% scenario is 0.4s. As the LIMERIC mixing ratio increases to 20% and then 80%, the IPG values at the first distance bin become 0.5s and 1s, respectively. The primary reason for the performance degradation of the CAM-DCC vehicles is that the default LIMERIC algorithm targets a high CBP (the default value is 76%), which drives CAM-DCC vehicles into more restrictive congestion control states.

Our previous work has also demonstrated that such performance degradation reduced in a specific scenario through a careful manual selection of LIMERIC's CBP target. The ideal target is dependent, however, on vehicle density and mixing ratio. This raises the question, whether the target can be automatically adapted to the network scenario so that CAM-DCC performance degradation is limited in all scenarios, if not eliminated.

III. TARGET ADJUSTMENT MECHANISM

In this section, we present a CBP target adjustment mechanism that automatically adjusts the CBP target of LIMERIC vehicles according to vehicle density and mixing situation of

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[2] PER is defined as the ratio of the number of missed packets at a receiver from a particular transmitter to the total number of packets sent by that transmitter. IPG is defined as the elapsed time between two consecutive successful packet receptions from a particular transmitter.

the two algorithms in a network, to reserve sufficient channel capacity for CAM-DCC and thereby limit the performance degradation to a desired level. As the basis of the proposed mechanism, we first present the theoretical results of the steady-state CBP of a mixed network.

A. *Steady-state CBP of a mixed network*

Assume that the total number of vehicles within the same interference range in a mixed network is $K = K_{limeric} + K_{camdcc}$, where $K_{limeric}$ denotes the number of the LIMERIC vehicles, and K_{camdcc} denotes the number of the CAM-DCC vehicles. The transmission rate of a vehicle j, denoted by r_j ($j = 1, 2, ..., K$), can be modeled as a fraction of the total channel capacity. Thus, the fraction of the network capacity allocated in aggregate to all K vehicles, represented in the number of transmitted messages per second, is $r_C(k) = \sum_{j=1}^{K} r_j(k)$. For mixed networks, r_C can be rewritten as:

$$r_C = r_{limeric}K_{limeric} + r_{camdcc}K_{camdcc} \tag{1}$$

Based on Eq. 7 in [9], $r_{limeric}$ is determined by

$$r_{limeric} = \frac{\beta(r_{target} - r_{camdcc}K_{camdcc})}{\alpha + \beta K_{limeric}} \tag{2}$$

where $r_{target} - r_{camdcc}K_{camdcc}$ is the actual CBP target of the LIMERIC vehicles in a mixed network. Due to CAM-DCC vehicles' sharing of the channel capacity, LIMERIC vehicles have to first exclude the channel load contribution of CAM-DCC vehicles from the predefined target. α and β are adaption parameters that control LIMERIC's stability, fairness and convergence. Applying Eq. 2 into Eq. 1, we have

$$r_C = r_{target} - \frac{\alpha}{\beta} r_{limeric} \tag{3}$$

r_C presents the number of transmitted messages per second on the channel. There is a one-to-one relationship between r_C and the measured CBP [9]. According to this mapping, Eq. 3 can be written as

$$CBP_C = CBP_{target} - \frac{\alpha}{\beta * \delta} r_{limeric} \tag{4}$$

where CBP_{target} is the CBP target that LIMERIC vehicles use in their rate adaptation equation; CBP_C is the CBP of a mixed network when LIMERIC vehicles reach to the steady state; δ represents the near-linear mapping from the number of messages per second to CBP.

B. *Mechanism design*

The proposed target adjustment mechanism consists of four main components:

1) Estimating the number of vehicles within the interference range
2) Estimating the pure CAM-DCC state, i.e., the CAM-DCC state at which a CAM-DCC vehicle would operate if all the vehicles use CAM-DCC algorithm
3) Determining new CBP targets for LIMERIC vehicles
4) Sharing new CBP targets with other LIMERIC vehicles over a two-hop range

The LIMERIC vehicles run this mechanism periodically and synchronously. With a relatively short period, each LIMERIC vehicle is able to collect the required information frequently and then react to changes in channel condition in a timely manner. The synchronous operation[3] ensures the LIMERIC vehicles within the same interference range observe the same channel condition and mixing situation at the same time and then adjust to similar targets. The details will be described in the following. Table II lists the notations used in the mechanism description.

TABLE II: Notations used in the mechanism description

Notation	**Description**
$r_{limierc}$	The steady-state transmission rate of LIMERIC vehicles
r_{camdcc}	The steady-state transmission rate of CAM-DCC vehicles
R	The estimated LIMERIC's mixing ratio
K	The estimated number of vehicles within the interference range
$r_{camdcc}^{table}[\cdot]$	The function returns the corresponding transmission rate for an input CAM-DCC state according to Table I
$mapToTxCount(\cdot)$	The function maps the measured CBP to the number of transmissions generating such a CBP value
$mapToCBP(\cdot)$	The inverse function of $mapToTxCount(\cdot)$
$level_{deg}$	The degradation level is allowed by the CAM-DCC vehicles in a mixed network
$CBP_{desired}^{table}[\cdot]$	Given a state which CMA-DCC vehicles desire to operate at, this function returns the CBP value to which the channel load should converge

*1) **Estimating the number of vehicles in the interference range**:* First, a receiver is assumed to be able to distinguish whether the sender of the received packet is using the LIMERIC or the CAM-DCC algorithm. There could be several methods to identify the sender's algorithm type, e.g., the sender can explicitly indicate its algorithm type via one bit in its packet header, or the receiver can implicitly tell the algorithm type by checking the received packet's header structure, since a LIMERIC packet piggybacks the shared CBP values in its packet header, while a CAM-DCC packet does not. With such a capability, a receiver is able to count the number of the LIMERIC vehicles and the CAM-DCC vehicles within its one-hop range separately, and then estimate the LIMERIC's mixing ratio. Meanwhile, a receiver can also infer the sender's transmission rate based on the packet sending time and the packet id piggybacked in each received packet. One simple implementation for doing so could be: 1) For each sender, the receiver keeps recording the packet sending time and the packet id of the latest received packet from that sender; 2) Once a new packet from that sender is received, the receiver respectively examines the differences in packet sending time and the packet id between this packet and the latest packet from the same sender; 3) Based on the number of packets transmitted during the elapsed time, the transmission rate of the sender can be estimated.

We believe that this mixing ratio within the reception range is also a good estimation for the mixing ratio within the interference range. For estimating the number of vehicles within the interference range, we exploit the locally measured CBP and the estimated LIMERIC's mixing ratio. As aforementioned, there exists a one-to-one near-linear mapping between the measured CBP and the number of transmissions contributing to this CBP value. $mapToTxCount(CBP)$ implements this mapping as a function of the measured CBP. If assuming K

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[3] Synchronization can be achieved via GPS synchronization techniques.

Algorithm 1 CBP Target Adjustment Mechanism

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1:  Input: $r_{limeric}$, $r_{camdcc}$, $CBP_{measured}$, $R$, $level_{deg}$ $r^{table}_{camdcc}[\cdot]$, $maxTolerateTx[\cdot]$
2:  Output: $CBP^{'}_{T}$
3:  $CBP^{'}_{T} = CBP_{T}$
4:  $K \cdot (r_{limeric} \cdot R + r_{camdcc} \cdot (1 - R)) = mapToTxCount(CBP_{measured})$
5:  Estimate the pure CAM-DCC state index, $dcc\_stateIndex\_pure$
6:  $dcc\_stateIndex\_exp = dcc\_stateIndex\_pure - level_{deg}$
7:  if $mapToTxCount(CBP^{table}_{desired}[dcc\_stateIndex\_exp]) < r^{table}_{camdcc}[dcc\_stateIndex\_exp] \cdot K)$ then
8:      $CBP_{desired} = mapToCBP(r^{table}_{camdcc}[dcc\_stateIndex\_exp] \cdot K)$
9:  else
10:     $CBP_{desired} = CBP^{table}_{desired}[dcc\_stateIndex\_exp]$
11: end if
12: $r^{exp}_{limeric} = (mapToTxCount(CBP_{desired}) - r^{table}_{camdcc}[dcc\_stateIndex\_exp] \cdot K \cdot (1 - R))/(K \cdot R)$
13: $CBP^{'}_{T} = CBP_{desired} + \frac{\alpha}{\beta} \cdot r^{exp}_{limeric}$
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vehicles are within the interference range, we then have

$$r_{limeric} \cdot K \cdot R + r_{camdcc} \cdot K \cdot (1 - R) = mapToTxCount(CBP)$$

The terms on the left side represent the number of transmissions sent by the LIMERIC and the CAM-DCC senders, respectively. They are expected to be equal to the total number of transmissions which contribute to the measured CBP. Here, $r_{limeric}$, r_{camdcc}, R and CBP can be obtained via local measurements. Note that $r_{limeric}$ and r_{camdcc} are estimated via the average rate. Thus, K can be computed from this equation, and then the number of the LIMERIC vehicles and the CAM-DCC vehicles are $K \cdot R$ and $K \cdot (1 - R)$, respectively.

2) ***Estimating the pure CAM-DCC state:*** In this step, all the vehicles in the network are assumed to use the CAM-DCC algorithm, and thus the CAM-DCC state of CAM-DCC vehicles (called pure CAM-DCC state) in this homogeneous network can be estimated. For each CAM-DCC state defined in Table I, the maximum number of vehicles which can be tolerated in that state is calculated through the upper bound of the corresponding CBP range and the defined transmission rate for that state. For example, the ACTIVE 1 state defines the transmission rate as 5 Hz and the corresponding CBP range as 30%-39%. The maximum number of vehicles tolerated in this state is $mapToTxCount(39)/5$. We then compare, in turn, K with the maximum number of vehicles tolerated in each defined state, starting from the RELEAXED state. The first state whose maximum number of tolerated vehicles is greater than K, will be selected as the pure CAM-DCC state.

3) ***Determine the new CBP target for LIMERIC vehicles:*** To drive the CAM-DCC vehicles to operate at a specific state, their measured CBP values have to fall into the CBP range associated with that state. In mixed networks, the LIMERIC vehicles and the CAM-DCC vehicles within the same interference range share a similar CBP value. Therefore, the CBP target is adjusted such that the LIMERIC vehicles' steady-state CBP is within the CBP range associated with the desired state. The choice of the new CBP target also depends on the allowed degradation level, which indicates how much degradation the CAM-DCC vehicles can accept in a mixed network in terms of CAM-DCC states[4]. With the estimated pure CAM-DCC state and the allowed degradation level, the LIMERIC vehicles can estimate the expected state of CAM-DCC vehicles in the mixed network, denoted as dcc_state_exp.

Given the expected CAM-DCC state, the LIMERIC vehicles will try to push their steady-state CBP into the associated CBP range of this state. To achieve this goal, the LIMERIC vehicles have to determine to what exact value within this range the CBP will converge at the steady state. With considering the measurement variation of CBP, we conservatively designate the middle point of the CBP range as the steady-state CBP for the associated CAM-DCC state. However, if $mapToTxCount(CBP^{table}_{desired})$ is less than the number of transmissions generated by K vehicles transmitting at rate $r^{table}_{camdcc}[dcc\_stateIndex\_exp]$, the designated CBP is replaced by $mapToCBP(r^{table}_{camdcc}[dcc\_stateIndex\_exp] \cdot K)$ as shown in line 8 in Algorithm 1. This is because if the number of transmissions corresponding to the designated CBP ($mapToTxCount(CBP^{table}_{desired})$) is smaller, it indicates that the transmission rate of the LIMERIC vehicles is potentially smaller than that of the CAM-DCC vehicles (i.e., $r^{table}_{camdcc}[dcc\_stateIndex\_exp]$), which can further result in a performance degradation of the LIMERIC vehicles. The final designated CBP is denoted as CBP_{desire}.

After adjusting the CBP target, the equation in line 12 in Algorithm 1 is used to predict the LIMERIC vehicles' transmission rate. In this equation, the term $mapToTxCount(CBP_{desired})$ is considered as the resource which is allocated to all the vehicles within the interference range. The term $r^{table}_{camdcc}[stateIndex] \cdot K \cdot (1 - R)$ denotes the resource share of the CAM-DCC vehicles. Thanks to the PULSAR mechanism, the LIMERIC vehicles can fairly share the resource. Thereby, the rest portion of the resource is evenly allocated to $K \cdot R$ LIMERIC vehicles. According to Eq. 4, the new CBP target is determined as $CBP^{'}_{T} = CBP_{desired} + \frac{\alpha}{\beta} \cdot r^{exp}_{limeric}$. Note that due to the errors in measurement and prediction, it is possible that in some cases, the new target could lead the LIMERIC vehicles to transmit at a lower rate than the expected rate of the CAM-DCC vehicles (i.e., $r^{table}_{camdcc}[dcc\_stateIndex\_exp]$). If such a case is detected, the LIMERIC vehicles start to transmit at rate $r^{table}_{camdcc}[dcc\_stateIndex\_exp]$ despite the calculated transmission rate.

4) ***CBP target sharing:*** To preserve the fairness between LIMERIC vehicles, a CBP target sharing mechanism is applied to share the CBP target over two-hop neighbors. Each LIMERIC vehicle inserts its own CBP target ($targetCBPSelf_{pkt}$), the received CBP target from its one-hop neighbors ($targetCBP1Hop_{pkt}$), and the index of the CAM-DCC state (idx_exp_{pkt}) at which the neighboring CAM-DCC vehicles expect to operate. Via the PULSAR mechanism, the sender's local CBP measurement ($CBPSelf_{pkt}$) and the received CBP value from its one-hop neighbors ($CBP1Hop_{pkt}$) are also shared with other LIMERIC vehicles.

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[4] For instance, the state of the CAM-DCC vehicles in a mixed network is the ACTIVE 2 state, while the pure CAM-DCC state is the ACTIVE 1 state. The degradation level in this case is one.

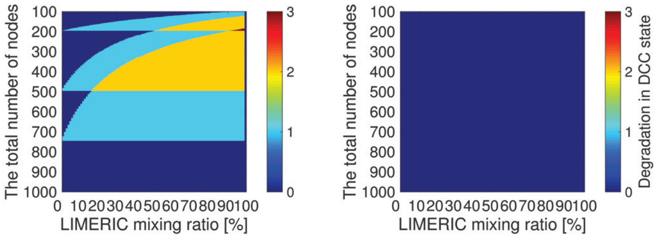
Once a new LIMERIC packet arrives, the LIMERIC receiver extracts the values of $CBPSelf_{pkt}$ and $CBP1Hop_{pkt}$ from the packet, and then compare them with the locally stored values of $CBP1Hop_{local}$ and $CBP2Hop_{local}$. Only if the CBP values piggybacked in the packet is larger, the CBP targets in the packet are considered being accepted. The rationale behind this design is that the senders in a more channel-congested region (i.e., the region with higher CBP) hold a higher priority for being assisted to control the congestion, and thereby their CBP targets should be considered with priority as well. The LIMERIC receiver then examines the CBP target piggybacked in the packet. Recall that a new CBP target is determined according to which state the neighboring CAM-DCC vehicles are desired to operate at. Different desired CAM-DCC states can result in different CBP targets. We believe it is fairer to separately consider the CBP targets for different desired CAM-DCC states. $targetCBP1HopArray$ and $targetCBP2HopArray$ are used to hold the CBP targets for different CAM-DCC states over a two-hop range. For the same CAM-DCC state, if the CBP target in the received packet is smaller, the held CBP target is updated to the value in the packet. The reason for selecting the smaller CBP target is that a vehicle with a higher CBP tends to determine a smaller CBP target. At the end of each target sharing window, each LIMERIC vehicle decides the new CBP target by two steps: 1) Find the most restrictive CAM-DCC state corresponding to the received CBP targets; 2) Select the minimum value of CBP targets for that state.

IV. PERFORMANCE EVALUATION

A. Evaluation in MATLAB simulations

In the MATLAB evaluation, the nodes are deployed in a relatively small area so that all the nodes observe the same channel condition. The total number of the nodes in the network increases from 100 to 1000, and for each node density, the LIMERIC's mixing ratio varies from 0% to 100%.

As shown in Fig. 2a, without adjusting the CBP target, the CAM-DCC vehicles degrades one to two levels in almost all the scenarios where the total number of nodes is less 800. This is because, in these scenarios, the LIMERIC vehicles attempt to push the CBP towards a comparatively high target. While reacting to the increasing CBP values, the CAM-DCC nodes operate at more restrictive states. However, as the node density increases, the degradation level decreases. This is because, in these high node density scenarios, the CBP is high enough such that even without the participation of LIMERIC nodes, the CAM-DCC nodes already operate at a highly restricted state. Fig. 2b shows the results of simulations where the proposed CBP target adjustment mechanism is applied and the CAM-DCC nodes only allow zero-level degradation. It is observed that across many different combinations of node density and LIMERIC's mixing ratio, the proposed mechanism helps the CAM-DCC nodes to eliminate the performance degradation. This is because the proposed mechanism estimates the pure CAM-DCC state based on the collected information and the LIMERIC's CBP target is adjusted in a way such that the steady-state CBP is within the CBP range associated with the pure CAM-DCC state. Therefore, the performance degradation of the CAM-DCC nodes is eliminated.



(a) (b)

Fig. 2: Performance degradation of CAM-DCC vehicles in terms of DCC state, allowing zero-level degradation: (a) without target adjustment; (b) with target adjustment

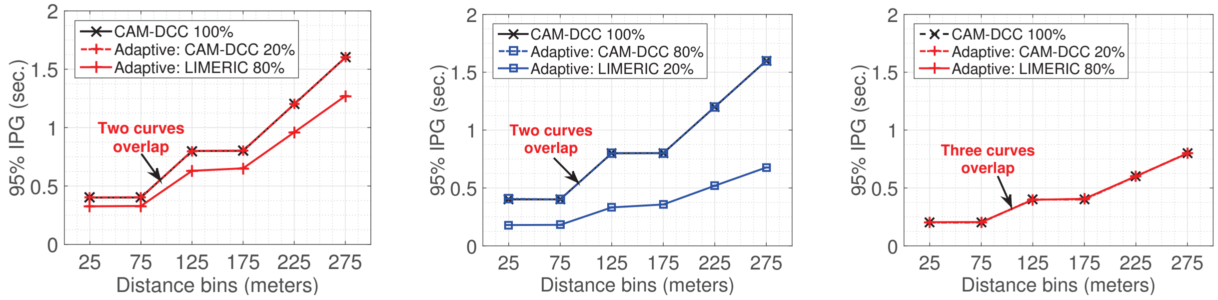
B. Evaluation in ns-2 simulations

In this subsection, the performance of the proposed mechanism is evaluated via ns-2 simulations of a highway scenario. The highway is configured as 4 km long and 3 lanes in each direction. The middle part of the road is set to be a winding section of linear length 375 m. The vehicle's average speed is around 30 m/s. The Nakagami model is used to model the wireless channel fading and the model parameters are the same in [13]. The transmission power is set to 10 dBm in order to create a typical 500 m DSRC transmission range in the simulation. More details of the simulation configurations can be found in [11]. Note that all the presented results are based on transmissions carried out on the winding part of the road.

Fig. 3a shows the 95th percentile IPG results of a set of simulations with 500 vehicles and the LIMERIC's mixing ratio as 80%. Similar to the observations from the MATLAB simulations, with the proposed mechanism, the results of the CAM-DCC vehicles in the mixed network only differ by 1.4%, comparing to the results of the homogeneous CAM-DCC network (CAM-DCC 100% scenario). Recall that the degradation was two-level before the target adjustment is applied (see Fig. 1b). Although the LIMERIC vehicles adjust their CBP target with the purpose of controlling the performance degradation of the CAM-DCC vehicles, the LIMERIC vehicles still outperform the CAM-DCC vehicles by $\sim 20\%$.

1) Changing LIMERIC's mixing ratio: In order to investigate the performance of the proposed mechanism in mixed networks with different LIMERIC's mixing ratios, a set of simulations with the LIMERIC's mixing ratio as 20% is conducted. Similar to the observations from Fig. 3a, Fig. 3b shows that the performance degradation of the CAM-DCC vehicles is eliminated with the target adjustment, while the LIMERIC vehicles still perform better.

2) Changing the number of vehicles: As shown in Fig 3c, similar results are observed for the simulations with 250 vehicles and the LIMERIC mixing ratio as 80%. In this scenario, the degradation decreases to less than 0.1%. Note that in this scenario, the LIMERIC vehicles behave similarly to the CAM-DCC vehicles. It is because in this case, the LIMERIC vehicles conservatively determine a new CBP target which can help the CAM-DCC vehicles to control performance degradation but let the LIMERIC vehicles transmit at a lower rate than the CAM-DCC vehicles. Recall that the proposed



(a)

(b)

(c)

Fig. 3: 95th percentile IPG for the mixed networks: (a) zero-level degradation, 500 vehicles with 80% LIMERIC; (b) zero-level degradation, 500 vehicles with 20% LIMERIC; (c) zero-level degradation, 250 vehicles with 80% LIMERIC

mechanism can detect such a situation and then force the LIMERIC vehicles to transmit at the same rate as the CAM-DCC vehicles in order to prevent the unfairness between the LIMERIC vehicles and the CAM-DCC vehicles.

3) Different allowed degradation levels: Fig. 4 illustrates the CBP target of a LIMERIC vehicle which stands in the middle region of the road. It shows that the CBP target of the simulation allowing zero-level of degradation is about 13% lower than that of the simulation allowing one-level of degradation. Generally speaking, in order to meet a higher requirement for the performance degradation, LIMERIC vehicles have to adjust to a lower target and then transmit at a lower rate. This is because the pure CAM-DCC state is normally more relaxed than the CAM-DCC state of CAM-DCC vehicles in a mixed network. Towards a more relaxed state, the CBP has to be driven to a range of smaller values.

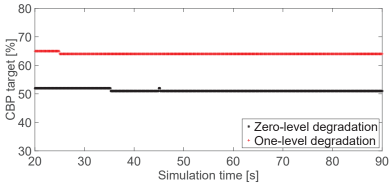


Fig. 4: CBP target for allowing zero-level degradation and one-level degradation

V. CONCLUSION AND FUTURE WORK

We presented a CBP target adjustment mechanism for adjusting the CBP target of LIMERIC vehicles to eliminate or reduce the performance degradation of CAM-DCC vehicles to a specified level. Simulation results indicate that the performance degradation of the CAM-DCC vehicles is virtually eliminated when the target adjustment is used, while the LIMERIC vehicles still maintain similar or better performance. When no CAM-DCC vehicles are around, LIMERIC reverts back to its default target and performance. This suggests that it is feasible to design vehicular congestion control algorithms so that a new algorithm can be gradually introduced without significantly degrading the performance of legacy vehicles.

Future work should also evaluate the performance of the proposed mechanism in different propagation environments and study how inaccurate estimation and prediction in the mechanism can compromise its effectiveness.

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