Cooperative Wireless Congestion Control for Multi-Service V2X Communication

Mohammad Irfan Khan[†], Miguel Sepulcre[‡], Jérôme Härri[†]
[†]EURECOM, Sophia-Antipolis, France. E-mails: {khanm,haerri}@eurecom.fr
[‡]Universidad Miguel Hernandez de Elche (UMH), Spain. E-mail: msepulcre@umh.es

***Abstract*—Wireless congestion control and resource allocation for 802.11p based V2X safety communication have been widely investigated for a single Cooperative Awareness service, considering homogeneous resource requirement per vehicle. Future cooperative connected vehicles, will have heterogeneous capabilities and communication needs, which existing congestion control mechanisms have not fully addressed.**

In this paper, we analyze issues with the channel congestion control protocol standardized in Europe by ETSI, regarding distributed resource allocation for heterogeneous number of services and message types per vehicle. We present a cooperative congestion control mechanism to orchestrate channel resource among a mixed distribution of vehicles with diverse resource requirements under channel congestion. Simulation based evaluation using standardized safety messages show the application performance improvement rendered by our proposed mechanism, compared to the standardized protocol.

I. Introduction

Vehicular networks are being designed to increase road safety by increasing the driver's and vehicle's awareness of the surrounding through the wireless exchange of information. To this aim, vehicles will periodically exchange awareness information via safety V2X (Vehicle-to-Everything) messages with neighboring vehicles, road users, road infrastructure and alike. This information can include ego status information such as position, speed, heading etc. in the so called Cooperative Awareness Messages (CAM) and information about emergency situations (emergency braking, traffic jams, etc.) in the so called Decentralized Environmental Notification Messages (DENM). Over the years, safety applications such as Lane Change Warning (LCW), Road Hazard Signaling (RHS), Longitudinal Collision Risk Warning (LCRW) etc. have been developed for initial a.k.a DAY 1 deployment.

Similarly, two leading technologies, IEEE 802.11p based DSRC/ITS-G5 and 3GPP LTE-V2X are likely to be deployed for V2X communication. In IEEE 802.11 based vehicular networks and Mode 4 of LTE-V2X[1], there is no centralized channel resource allocator, and nodes prevent channel saturation by limiting their ego channel usage. Limiting spatial channel usage via Transmit Power Control (TPC) has been proposed in [1]–[3] and temporal channel usage via Transmit Rate Control (TRC) has been presented in [4]–[6]. Wireless congestion control protocols have been standardized by SAE in the USA [7] and by ETSI [8]–[10], known as Decentralized Congestion Control (DCC) in Europe. In existing approaches, a common method of ensuring fairness is allocating similar channel resource to neighboring vehicles facing similar channel condition, considering only a single type of safety message i.e. CAM/BSM for DAY 1 deployment.

[1]Although this paper analyzes decentralized congestion control and resource allocation on top of 802.11p, but the approach can be extended to LTE-V2X Mode 4.

In future or DAY 2 scenario, vehicles will have multiple sensors serving multiple applications such as High Precision Positioning, HD map exchange, Collective Perception, Maneuver Coordination, Cooperative Adaptive Cruise Control (CACC), thus transmitting a variety of messages in the channel. ETSI has already started standardizing messages such as Collective Perception Message (CPM) [11], Maneuver Coordination Message (MCM) [12] and other safety messages for future deployment. Therefore, wireless congestion control mechanisms designed for a single message such as CAM/BSM may not be sufficient in future.

The first challenge of resource allocation for multiple services is to balance the needs of safety services competing for channel resource inside a vehicle, termed as 'In-Vehicle Resource Allocation', as analyzed in our previous paper [13] and other recent studies [14], [15]. Similarly, some vehicles will be more autonomous or 'advanced' than others, having more services and higher channel resource requirement compared to legacy vehicles. Therefore, a bigger challenge is how to decentrally allocate channel resources heterogeneously among neighboring vehicles with different number of services and diverse channel resource requirement per vehicle. We address this challenge in this paper.

We propose a distributed mechanism, on top of ETSI Adaptive DCC [8], where vehicles cooperate and sacrifice resource from their lower priority communication in order to facilitate higher priority communication by neighboring vehicles. Our contributions are three folds: (i) We present the problem of decentralized channel congestion control as a mechanism of distributed resource allocation; (ii) We demonstrate that equal resource allocation among neighboring vehicles may be problematic when the resource demand is non-homogeneous; (iii) We propose a distributed and cooperative mechanism for heterogeneous channel resource allocation among vehicles, and evaluate its performance compared to standardized Adaptive DCC.

The rest of the paper is organized as follows: Section II presents briefly the channel congestion control mechanisms in the literature. Section III gives a brief overview of ETSI standardized DCC as a mechanism for congestion control and channel resource allocation. Section IV, presents the challenges of heterogeneous resource requirement by vehicles. Section V provides simulation based performance evaluation results, and lastly Section VI concludes the paper along with future perspectives.

II. Related Work

V2X channel congestion control has been widely investigated in the literature, with mechanisms proposing to control the transmit power w.r.t channel load or Channel Busy Ratio (CBR) [1]–[3], while other studies have proposed controlling the transmit rate [4]–[6]. Similarly, some studies have proposed controlling both rate and power, such as [16]–[18].

Among the TRC mechanisms proposed in the literature, Linear Message Rate Control (LIMERIC) [4] has been modified and proposed in the ETSI Access DCC standard TS 102 687 [8]. With LIMERIC, each vehicle uses a linear feedback loop to periodically measure the CBR and iteratively adapt the Inter Transmit Time (ITT) or transmit rate to reach a target CBR. Transmit rate can also be controlled by reducing the generation of packets, a technique termed as awareness control. Studies on awareness control [19], [20], limit the channel load by transmitting CAM/BSM at a minimum required rate to satisfy an awareness metric, for example nodes with higher mobility transmit more and vice versa. The study [21], looks into optimizing the transmit rate and power for multiple applications, using a single awareness message. However, existing studies have not considered more complex scenarios, such as a diverse number of safety services/messages per vehicle, which will be a common scenario in future deployments.

Few recent studies [14], [15], [22] have analyzed channel congestion control with multiple safety messages for DAY 2. The study in [14] investigates CAM with CPM and demonstrates starvation of lower priority messages during channel congestion due to lack of resource to transmit both the messages. The study in [15] analyzes CAM and DENM, and shows similar starvation of CAM. Similar observation of starvation with multiple message types during channel congestion has been shown in [22].

Similarly, some studies have looked at allocating higher transmit rates to vehicles with higher demand. The paper [23], demonstrates a mechanism to allocate heterogeneous transmit rate limits to neighboring nodes using the LIMERIC, applying different rate control parameters to each node. However, the feasibility of the approach can be challenging in the ETSI ITS stack, as the ETSI Access DCC standard [24], specifies fixed parameters for the Adaptive DCC algorithm at the Access layer.

In this paper, we present a distributed resource allocation mechanism to distribute the available radio resources among vehicles with heterogeneous resource demands. It is a self-organizing mechanism that allocates more resources to vehicles having higher priority services, reducing the resources allocated to vehicles with lower priority services, while maintaining the channel load below saturation. The proposed mechanism operates on top of ETSI standardized Adaptive Access DCC [2]

III. Decentralized Congestion Control & Resource Allocation

A. Congestion Control

The goal of DCC is to limit the channel usage by each individual node and maintain the overall channel load below saturation. The control process in each node starts by measuring the channel load or CBR every 100ms. Based on the measured CBR, the control process sets the Channel Resource Limit (CRL) for the node, as indicated in ETSI standards [8], [9], [25]. The CRL is a unitless value, which can be expressed as the maximum fraction of time a node is allowed to transmit on the channel:

$$CRL = \frac{T_{on}}{T_{on} + T_{off}} \tag{1}$$

The CRL is used to control the transmit rate via queuing and flow control at the Access Layer, using additional queues above the EDCA queues. The flow control is done using a leaky bucket called 'Gate Keeper' below the DCC queues, and after each transmission of airtime T_{on} the bucket remains closed for a duration of T_{off}.

For example, let's say a node can use 0.4% of the channel. Thus, CRL = $T_{on} \div (T_{on} + T_{off})$ = 0.004. If the node transmits 300 Byte packets, T_{on} = 0.0004 sec (0.4 ms, 300 bytes), T_{off} will be 0.996 sec (99.6 ms), limiting the transmit rate to 10 Hz.

B. Distributed Resource Allocation

One of the goals of DCC is to ensure fairness while controlling the rate of individual nodes. In ETSI standards [9], [25], it is defined as: "Any ITS-S under the same channel conditions has an equal opportunity of accessing the radio channel for periodic messages, while maintaining a channel access margin to always allow the exchange of safety-critical event-based messages."

Therefore, the congestion control process reserves some channel capacity for high priority safety critical messages, and the rest of the channel capacity is to be equally shared among neighboring nodes facing similar channel conditions, as indicated in [25] as:

$$CRL = \frac{Channel\ Capacity\ Usage\ Limit}{\#Neighbors} \tag{2}$$

Thus DCC decentrally allocates the share of the channel capacity or Channel Resource Limit for each node. For example, let's say there are 5 nodes in the channel, as conceptually shown in Figure 1. After reserving 40% channel capacity for

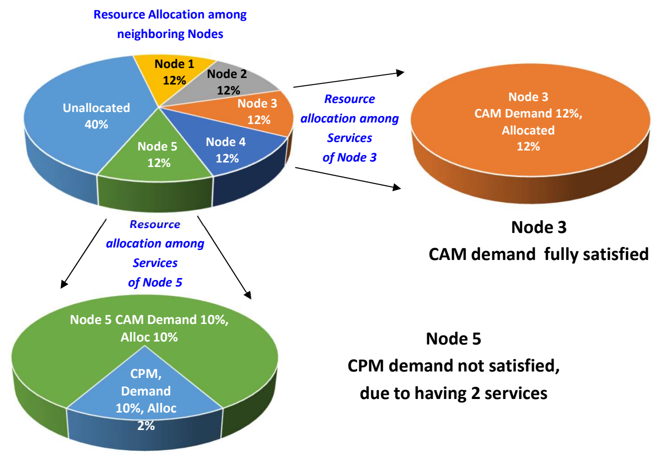

Fig. 1: Conceptual Representation of Resource Allocation

[2]Adaptive DCC ETSI TS 102 687 [8] is based on LIMERIC for the ETSI ITS Stack.

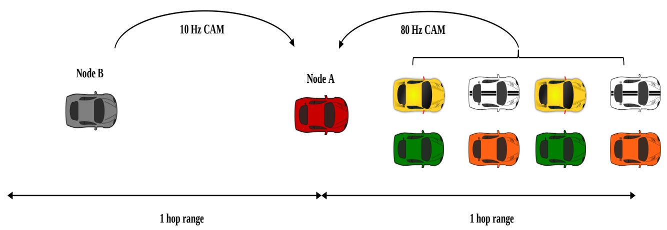

Fig. 2: Heterogeneous Resource allocation

high priority messages, the rest is equally shared among the 5 nodes, giving 12% CRL to each node, regardless of the number of service in each node. In this example, Node 3 emits only one type of message, i.e. CAM, which consumes the allocated 12% CRL. However, Node 5 emits CAM and CPM, and 12% is not sufficient for these 2 types of messages, and the CPM service is starved. In the next section, we present a mechanism to solve this problem, and allocate more channel resources to nodes with higher requirements.

IV. Heterogeneous Resource Allocation

In this section, we analyze and present our solution to the problem of DCC allocating equal channel resource to nearby vehicles regardless of the resource demand per vehicle. One method of approaching this problem can be analogous to a real-life road traffic scenario of pulling out of the road by normal vehicles to make way for emergency vehicles (such as ambulance or fire-truck) on the road, to facilitate its passage. Using this analogy, a node which is facing resource scarcity to transmit its higher priority messages announces its shortage to its 1-hop neighbors sharing the channel.

When the channel load is near the channel usage limit and the resource allocated to a node by DCC is insufficient to satisfy all its applications, our proposed solution allows that the node surpasses the DCC allocated resource quota only for its messages of highest priority P. Thanks to our proposed solution, the burden of the surpassed resource amount is equally shared by neighboring nodes within 1-hop distance, who sacrifice quota from their messages of priority less than P. The goal is to temporarily re-allocate resources from some nodes who are transmitting low priority messages, to other nodes who have a high priority message to transmit, while keeping the channel load same. Let's use an example to clarify the concept and aid the explanation which follows.

A. Example of Heterogeneous Resource Allocation

- Let's say the channel capacity usage limit is 100 msg/sec and currently 10 nodes are sending CAM of equal size at 10Hz each, totaling 100 msg/sec and fully using the channel as shown in Figure 2. DCC allocates to each node an equal resource quota of 10Hz.
- Out of those nodes, a node called Node A, additionally starts transmitting 10 Hz DENM, and DENM and CAM are of equal size. Using existing allocation of DCC, Node A will not be able to send any CAM, as DENM will fully use the resource quota of 10Hz per node.
- If we allow that Node A transmits 10Hz DENM, the total amount of transmitted messages per second would be 10% higher than the channel usage limit of 100 msg/sec. To avoid surpassing this limit while avoiding the starvation of CAM at Node A, our solution reduces the individual CAM transmit rate of all the 10 nodes, including A, by 10%, from 10Hz to 9Hz. Our solution therefore sacrifices 1Hz quota per node to liberate 10Hz capacity in the channel for the 10Hz DENM of Node A. Analogously, if any node transmits 5Hz CAM, it will sacrifice its CAM transmit rate by 10% to 4.5 Hz.
- The new message pattern in the channel is 90Hz CAM and 10Hz DENM, accommodated within the channel usage threshold of 100Hz. Similarly, when Node A stops transmitting DENM, all nodes stop sacrificing and things return as before.
- Lastly, all the processes occur dynamically in a distributed manner without any centralized control entity.

B. Heterogeneous Resource Allocation Mechanism

There are 3 steps in the process: i) The node with higher priority (HP) messages to transmit, i.e. higher priority node (HPN) calculates the amount of its resource shortage as a percentage of low priority (LP) messages in the channel. In order to accommodate its HP messages without surpassing the channel usage limit, a corresponding amount of LP messages have to be reduced in the channel. ii) The node announces its resource shortage as the calculated percentage, inside the header of transmitted HP messages. iii) Each neighbor within a 1-hop distance transmitting LP messages, i.e. lower priority nodes (LPN), and the HPN itself, reduce their individual rate of LP messages by that percentage.

The 3 steps are repeated every 100ms or its multiple, as long as the node with HP messages has a quota shortage.

Step 1: Resource Shortage Calculation

A key component of the approach is the percentage reduction of LP messages in the channel and by each node, such as 10% in the above example. It is calculated by the HPN, along with the resource quota shortage (QS) as:

$$QS = H + L * (1 - R) - QA \tag{3}$$

Where QA is the quota allowed by the Access DCC, H is the resource demanded by the HPN for its HP messages, L is the resource demanded by the HPN for its own LP messages, and R is the percentage of LP messages to be reduced in the channel. It is the same percentage reduction for the channel and each node within 1-hop range. It is calculated as:

$$R = \frac{QS}{LC} \tag{4}$$

In the above equation, LC corresponds to the total channel usage by lower priority messages from all nodes other than the HPN itself. Therefore, combining Eq. 3 and Eq. 4, QS can be obtained as:

$$QS = \frac{LC * (H + L - QA)}{L + LC} \tag{5}$$

In the case, where the node's allowed quota QA is fully consumed by LP messages, i.e. QA = L, then Eq. 5 becomes:

$$QS = \frac{LC * H}{QA + LC} \tag{6}$$

Thus, following the above example, using Hz or msg/sec as the unit of resource, LC = 90Hz (total CAM transmitted by all nodes other than the HPN), H = 10Hz (DENM demanded by the HPN), L = 10Hz (CAM transmitted by the HPN), QA = 10Hz (quota/message rate allowed for each node). Therefore, using Eq. 6, QS for Node A is (90 * 10) / (10+90) = 9Hz. Similarly, using Eq. 4, the percentage reduction R can be calculated as: QS/LC = 9/90 = 0.1 or 10%.

As mentioned earlier, the HPN i.e. Node A periodically updates R and announces the value of R inside the header of its HP messages. In the above example, for the second iteration, QS is calculated using Eq. 5 instead of Eq. 6, as the QA is 10, which is greater than L, which is 9. In the first iteration, every node including Node A, deceases 10% of LP messages, so in the second iteration the value of L is 9 for Node A. Therefore using Eq. 5, QA = 81(10 + 9 - 10)/(9 + 81) = 8.1 Hz. However, using Eq. 4, R remains the same, i.e. 8.1/81 = 0.1 or 10%. Therefore, the system remains stable if other conditions do not change, and all the nodes continue sacrificing 1Hz CAM.

However, for the HPN to use channel resource of an amount equivalent to QA + QS, it has to temporarily bypass the 'Gate Keeper' of the Access layer DCC, which allows QA resource to each node. Even if the 'Gate Keeper' functionality needs to be bypassed, the overall channel load remains unchanged, as resource is simply 'transferred' from nodes with LP messages to nodes with HP messages. In other words, the total channel usage and the channel load remain unchanged.

Step 2: Announcing Resource Shortage
The percentage reduction R is calculated by the HPN, as it cannot be calculated by the LPNs, because the value of LC or amount of channel usage due to LP messages is unique to the HPN. The value of LC may not be same for all of its 1-hop neighbors due to hidden nodes and asymmetric spatial distribution of channel load and type of messages creating the channel load. As shown in Figure 2, Node B from its position cannot determine the 90Hz (or its equivalent percentage) value of LC for the HPN, i.e. Node A.

Therefore, whenever the HPN faces a quota shortage, it can announce the value of R in the header of its HP messages, which acts as a control information for the LPNs to reduce the percentage of their LP messages.

Step 3: Resource Sacrifice by Nodes with Lower Priority Messages
As long as any LP node k, receives a HP message containing a value of R greater than 0, it sacrifices R% of resource from its LP messages. Therefore, each HPN periodically re-calculates R and announces it inside the header of its HP messages. If there are more than 1 HP neighboring nodes, the LP node k, sums up the R_i% for each of those N number of HPNs and reduces the resource quota L_k of its low priority messages, according to:

$$L_k = max(0, L_k * (1 - \sum_{i=1}^{N} R_i)) \qquad i \neq k \tag{7}$$

If a node has no more LP messages to sacrifice, its quota of LP messages becomes 0. Additionally, if the difference of priority levels or Traffic Class (TC), between the HP message and LP messages, i.e. TC_{HP} - $TC_{LP} > 1$, and if the node has quota for other low priority messages, then it starts sacrificing from that resource quota, until it has not sacrificed its share of quota of messages of priority equal to that of the HP message which is requesting the sacrifice. For example, if a node is sacrificing LP messages to allow more DENM from neighboring nodes in the channel, it first starts reducing resource quota of its CPM. If the resource for CPM becomes 0, then it can reduce its quota of CAM and so on, considering that the priority of DENM > CAM > CPM.

V. Performance Evaluation

In this section we present the necessity and feasibility of heterogeneous allocation firstly using a static scenario to analyze the functionality of our proposed mechanism at a granular scale. Afterwards we analyze using a bi-directional sub-urban highway scenario. We compare the performance of ETSI Adaptive DCC as specified in TS 102 687 [8], and our proposed heterogeneous resource allocation, in terms of message transmit rate required and allowed, with heterogeneous number of services i.e. resource demand among the vehicles.

Each node is equipped with ITS-G5 transmitters and the ETSI ITS stack. We use the iTETRIS simulator [26], which has a full ITS-G5 protocol stack implemented on top of NS-3. The wireless channel contains path-loss, shadowing and fading effects and is modeled according to Cheng and Stancil propagation model [27]. Each graph is an average of 40 to 50 simulation runs using random seeds. The confidence intervals are small and have not been plotted for the sake of readability of the curves. The simulation parameters are shown in Table I.

A. Evaluation with Static Scenario

In this first scenario, there are 160 static nodes, all visible to each other and transmit 300 Byte CAM at 10 Hz during 30 seconds. Moreover, few nodes out of those 160, additionally transmit 450 Byte 10 Hz DENM between seconds 10 and 20. Therefore, there are two groups of nodes in this scenario, i.e. nodes transmitting only CAM and nodes transmitting CAM and DENM. For the analysis and evaluation of this paper, DENM are not forwarded and simulating exact DENM emission conditions i.e. detecting an accident or road hazard, are not primordial for the performance evaluation in this paper.

TABLE I: Simulation Parameters

Parameter	Value
Transmit Rate	CAM 10 [Hz] & triggered, CPM 1-5 [Hz] DENM 10 [Hz]
Transmit Power	23 dBm
DataRate	6 Mbps
Packet Size	CAM 300 Bytes, DENM 400, CPM 650 Bytes
Packet Priority	DENM: (TC1), CAM (TC2), CPM (TC3)
Mobility	Static & Gauss Markov, 4 by 4 lane 10km highway, 10-50 veh/lane/km Speed: 70-90kmh
PHY and MAC	ITS-G5 802.11p in 5.9 GHz (10 MHz Control Channel)
Fading	Cheng and Stancil
Preamble Detection Threshold	- 92 dBm
Performance Indicators	Tx Rate, Channel Resource, Channel Load Avg 40 - 50 runs

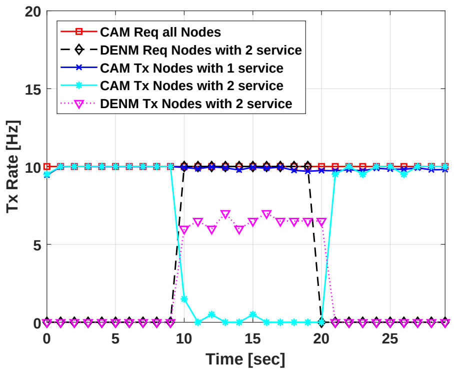

Fig. 3: Equal resource allocation by DCC

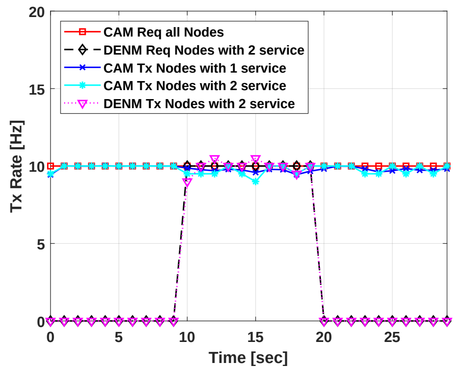

Fig. 4: Heterogeneous resource allocation (few DENM transmitters)

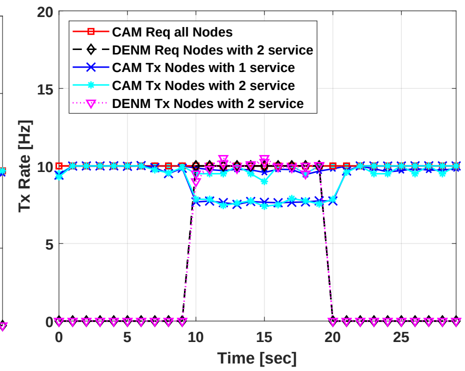

Fig. 5: Heterogeneous resource allocation (more DENM transmitters)

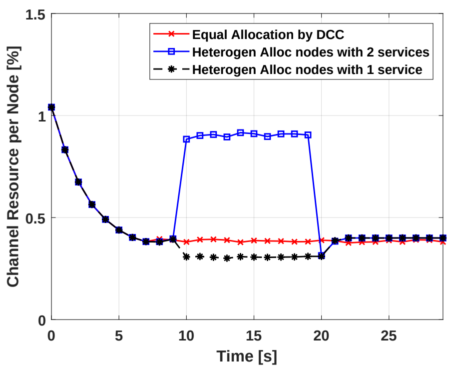

Fig. 6: Channel Resource per Node

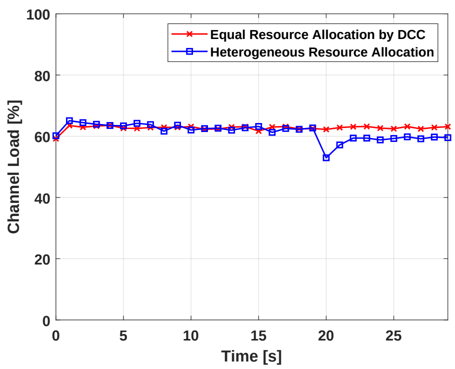

Fig. 7: Channel Load Static Scenario

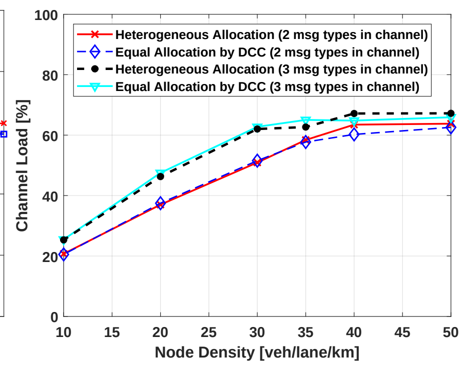

Fig. 8: Channel Load Dynamic Scenario

Figure 3 shows the Tx Rate demanded and allowed by Adaptive DCC. The first group of nodes that demand only CAM are able to transmit 10Hz CAM throughout the 30 seconds. The second group of nodes, also attempt to transmit 10 Hz CAM during 30 seconds. However, between 10 and 20 seconds when those nodes additionally attempt to transmit 10Hz DENM, they can only transmit 6-7Hz DENM and no CAM at all.

This phenomena can be explained using Figure 6, which shows the channel resource allocated to each node. After the first 10 seconds when the system stabilizes, each node is allocated 0.4% of channel resource. Considering 6 Mbps data rate, 0.4% allows a transmission of 0.004*750000 Bytes/sec = 3000 Bytes/sec. This resource quota can be used to transmit 300 Byte CAM at 10Hz or 450 Byte DENM at 6.67 Hz, which is exactly shown in Figure 3. As DCC maintains absolute priority of Traffic Class during flow control, DENM takes all the available transmission opportunities. As a result, nodes attempting to transmit CAM and DENM are not able to transmit any CAM between 10 and 20 seconds.

The channel load is maintained at around 64%, as shown in Figure 7. This demonstrates that Adaptive DCC maintains the channel load by allocating a fixed channel resource quota per node, which does not depend on the type or priority of the messages, or the number of service per node.

Figure 4 shows the performance of the same static scenario, using heterogeneous resource allocation on top of Adaptive DCC, described in the previous section. In this scenario, out of the static 160 nodes, only 2 nodes transmit 10 Hz DENM of 450 Bytes between 10 and 20 seconds, totaling 2*10*450=9000 Bytes/sec. The first significant improvement obtained by heterogeneous allocation is that nodes requesting 10Hz DENM are allowed to transmit 10 Hz, unlike the previous case of equal resource allocation by DCC where they could only transmit 6-7Hz DENM. To enable the transmission of 10Hz DENM by the 2 nodes, our proposed mechanism equally reduces the CAM transmission rate of all the 160 nodes. This reduction is equal to 9000/160 = 56.25 Bytes/sec, which is just 0.2 Hz reduction of 300 Byte CAM between 10 and 20 seconds, as shown in Figure 4. Consequently, the vehicles are able to successfully transmit their DENM, while all vehicles just experience a (nearly) negligible reduction of CAM.

Figure 5 considers the scenario where 20 out of 160 nodes transmit 10 Hz DENM. Considering DENM of 450 Bytes, this scenario requires the transmission of a total DENM footprint of 90000 Bytes/sec. This is equivalent to 2Hz CAM sacrificed by each of the 160 nodes. Therefore, an exact amount of channel resource is sacrificed by nodes with lower priority messages, which is fully used up by other nodes to transmit their higher priority messages without any loss of channel resource or transmit opportunity. Figure 6 also shows how the heterogeneous allocation allows that nodes with CAM and DENM get higher channel resource, while nodes with only CAM sacrifice their resource between 10 and 20 seconds.

Lastly, it is important to note that, despite the ‘transfer’ of allocated resources from low to high priority nodes provided by our solution, the channel load is maintained at around 64%, as shown in Figure 7. However, at 20 seconds, there is a slight dip in channel load, as it takes around 1 second for the sacrificing nodes to realize that DENM are no longer transmitted, after which they continue transmitting 10Hz CAM.

B. Evaluation with Dynamic Scenario: 2 message types

In this sub-section we present results using a 4 lane by 4 lane bi-directional 10 km sub-urban highway, with vehicles moving between 70 to 90 km/h following a Gauss-Markov mobility model, for various levels of vehicle density, between 10 to 50 vehicle/lane/km. The maximum vehicle density corresponds to Level of Service F of the USA highway capacity manual [28]. Each simulation has been run with a particular vehicle density. In this scenario, all the nodes transmit CAM following triggering condition as specified by ETSI EN 302 637-2 [29]. Additionally 10% of nodes transmit DENM, in a burst of 100 DENM over a period of 10 seconds.

Figure 9 shows the performance of the two groups of nodes, i.e. with only CAM and with CAM and DENM, with transmit rate controlled by Adaptive DCC. At low vehicle density, the resource allocated by Adaptive DCC to each node is sufficient to transmit the required 5Hz CAM and 10Hz DENM. However, from a density of 30 veh/lane/km corresponding to 48% channel load (see Figure 8), the resource allocated by Adaptive DCC is not sufficient, degrading the performance of CAM and DENM. On the contrary, nodes emitting only CAM always achieve the full required transmit rate of 5Hz.

Figure 10 shows the performance when heterogeneous allocation is used on top of Adaptive DCC. Firstly, DENM always achieve the required rate of 10 Hz. At low channel load, when there is enough resource per node for 10Hz DENM and 5Hz

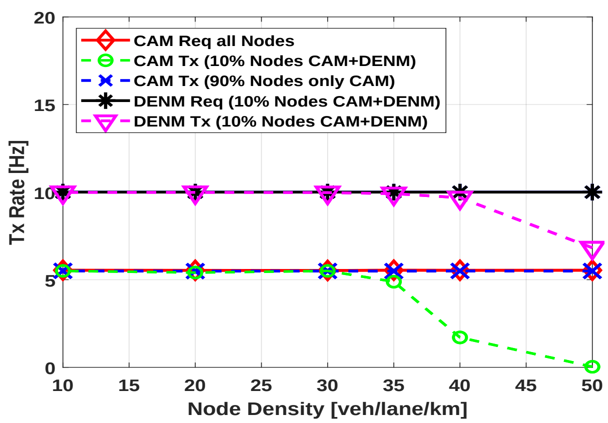

Fig. 9: Equal resource allocation by DCC (2 message types)

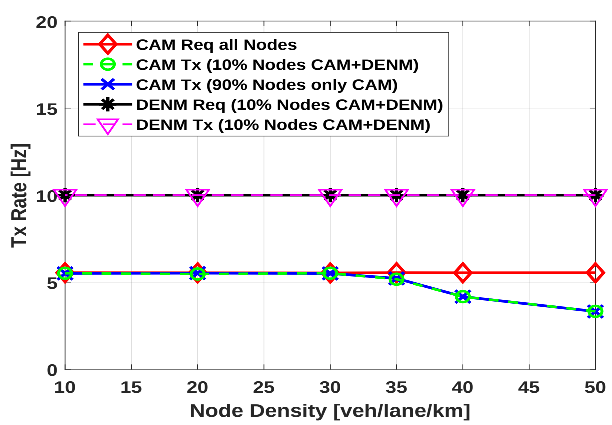

Fig. 10: Heterogeneous resource allocation (2 message types)

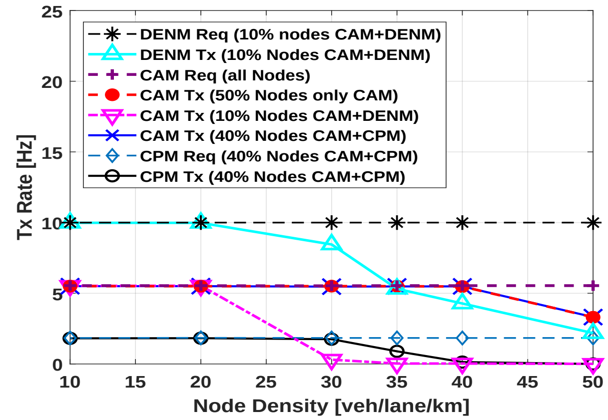

Fig. 11: Equal resource allocation by DCC (3 message types)

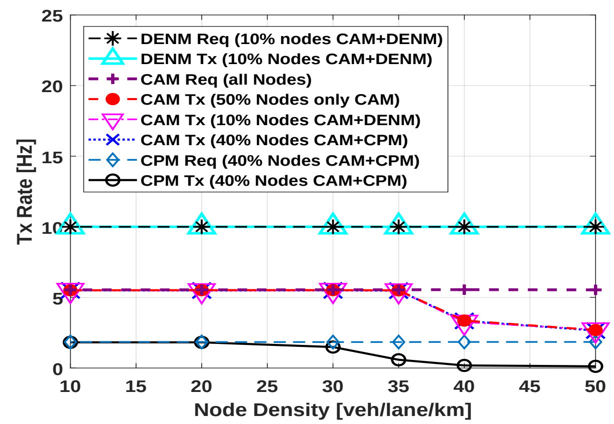

Fig. 12: Heterogeneous resource allocation (3 message types)

CAM, there is no CAM sacrifice by the nodes. The sacrifice begins only from a density of 30 veh/lane/km corresponding to around 48% channel load. At higher channel loads, as the resource per node decreases, the CAM sacrifice per node increases to ensure the 10 Hz transmit rate of DENM. Thus, unlike equal allocation by DCC, heterogeneous allocation prevents starvation of CAM of nodes transmitting two types of messages. Similarly, the 10 Hz required rate of DENM is always assured thanks to the sacrifice of a small amount of CAM by all the nodes sharing the channel.

C. Evaluation with Dynamic Scenario: 3 message types

In this sub-section we present results using the same highway scenario, but with three groups of nodes: 50% nodes transmitting only CAM, 40% nodes transmitting CAM and CPM, and 10% nodes transmitting CAM accompanied by a sudden burst of DENM for 10 seconds. Figure 11 shows the performance using Adaptive DCC, when nodes transmitting CAM and DENM suffer from a density higher than 20 veh/lane/km. The CAM Tx rate is almost zero at 30 veh/lane/km, while DENM Tx rate significantly drops as the vehicle density further increases. However, nodes transmitting only CAM or CAM and CPM achieve the required CAM Tx rate of 5Hz till a density of 40 veh/lane/km.

The performance is improved using heterogeneous allocation as shown in Figure 12. Firstly, DENM having the highest priority is allocated its required rate of 10 Hz regardless of the vehicle density. Similar to the previous cases, resource shortages occur from a node density of 30 veh/lane/km. The first message type which is sacrificed is CPM, as CPM has the lowest priority in these simulations. CAM and DENM still achieve the required Tx rate of 5 and 10 Hz at a density of 35 veh/lane/km, as CPM is being scarified. At 40 veh/lane/km, there is no more CPM to be sacrificed. Therefore, CAM being the message with the next higher priority in the channel, is gradually sacrificed by all the vehicles to maintain a Tx rate of 10 Hz DENM, demanded by vehicles requiring DENM transmission.

Thus, this mechanism starts by sacrificing messages having the lowest priority in the channel and continues the trend to allow transmission of higher priority messages by neighbors. Lastly, the heterogeneous allocation with 3 types of messages in the channel produces a similar channel load as Adaptive DCC, as shown in Figure 8.

VI. Discussion and Conclusion

ETSI V2X channel congestion control aims to prevent channel saturation by periodically measuring the channel load and controlling each vehicle's transmit rate, through an equal resource allocation strategy, regardless of the packet type, size or number of services per vehicle. Whereas, in future V2X scenarios, more advanced vehicles with higher sensing capabilities may transmit more types of messages, and demand higher channel resources than legacy vehicles.

In order to mitigate this problem of heterogeneous resource demand, we present a distributed protocol for vehicles with lower priority messages to sacrifice some of their resources and 'transfer' those to vehicles with higher priority messages facing a resource shortage. Simulation based evaluation using standardized safety messages shows the feasibility and agility of our proposed approach, improving the transmit rate of vehicles with higher priority messages by at least twice or more, compared to ETSI standardized congestion control protocol.

Although we evaluated the ETSI Adaptive congestion control protocol, but our approach can be easily extended to the SAE congestion control protocol standardized in the USA, which we will look in our future work. Similarly, our future work includes the analysis of scenarios where a persistent demand from high priority services may require sacrificing the lower priority services indefinitely. Solving this problem can be very challenging using static message priorities or Traffic Class, and our goal is to explore the use of dynamic prioritization of services.

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References

[1] M. Torrent-Moreno, P. Santi, and H. Hartenstein, "Distributed fair transmit power adjustment for vehicular ad hoc networks," in *2006 3rd Annual IEEE Communications Society on Sensor and Ad Hoc Communications and Networks*. IEEE, 2006.

[2] B. Kloiber, J. Harri, and T. Strang, "Dice the tx power—improving awareness quality in vanets by random transmit power selection," in *Vehicular Networking Conference (VNC), 2012 IEEE*.

[3] J. T. Willis, A. Jaekel, and I. Saini, "Decentralized congestion control algorithm for vehicular networks using oscillating transmission power," in *2017 Wireless Telecommunications Symposium (WTS)*. IEEE, 2017, pp. 1–5.

[4] J. B. Kenney, G. Bansal, and C. E. Rohrs, "Limeric: a linear message rate control algorithm for vehicular dsrc systems," in *8th ACM Workshop on Vehicular inter-networking (VANET), 2011*.

[5] T. Tielert, D. Jiang, Q. Chen, L. Delgrossi, and H. Hartenstein, "Design methodology and evaluation of rate adaptation based congestion control for vehicle safety communications," in *IEEE Vehicular Networking Conference (VNC), 2011*.

[6] S. Ruehrup, P. Fuxjaeger, and D. Smely, "Tcp-like congestion control for broadcast channel access in vanets," in *2014 International Conference on Connected Vehicles and Expo (ICCVE)*. IEEE, 2014, pp. 427–432.

[7] SAE, "SAE J j2735 dedicated short range communications (dsrc) message set dictionary," 2009.

[8] ETSI, "TS 102 687: Decentralized congestion control mechanisms for intelligent transport systems operating in the 5 ghz range, v1.2.1," 2018.

[9] ETSI, "TS 103 175 intelligent transport systems (its)," *Cross Layer DCC Management Entity for operation in the ITS G5A and ITS G5B medium, v1*, 2015.

[10] DRAFT, "ETSI TS 103 141 "intelligent transport systems," *Facilities Layer; Communication Congestion Control*, 2018.

[11] ETSI, "ETSI DRAFT TS 103 324 (2018)," *Intelligent Transport Systems (ITS); Collective Perception Service*.

[12] ETSI, "Etsi ts 103 561 intelligent transport systems (its); vehicular communication; basic set of application; maneuver coordination service," 2014.

[13] M. I. Khan, S. Sesia, and J. Härri, "In vehicle resource orchestration for multi-V2X services," in *VTC 2019 Fall, 90th IEEE Vehicular Technology Conference, 22-25 September 2019, Honolulu, Hawaii, USA*. [Online]. Available: http://www.eurecom.fr/publication/5990

[14] H.-J. Günther, R. Riebl, L. Wolf, and C. Facchi, "Collective perception and decentralized congestion control in vehicular ad-hoc networks," in *Vehicular Networking Conference (VNC), 2016 IEEE*.

[15] S. Kuhlmorgen, A. Festag, and G. Fettweis, "Evaluation of multi-hop packet prioritization for decentralized congestion control in vanets," in *2017 IEEE Wireless Communications and Networking Conference (WCNC)*, 2017.

[16] B. Kloiber, J. Härri, T. Strang, S. Sand, and C. R. Garcia, "Random transmit power control for dsrc and its application to cooperative safety," *IEEE Transactions on Dependable and Secure Computing*, 2015.

[17] M. Ruffini and H.-J. Reumerman, "Power-rate adaptation in high-mobility distributed ad-hoc wireless networks," in *Vehicular Technology Conference, 2005. VTC 2005-Spring. 2005 IEEE 61st*.

[18] R. Baldessari, D. Scanferla, L. Le, W. Zhang, and A. Festag, "Joining forces for vanets: A combined transmit power and rate control algorithm," in *6th international workshop on intelligent transportation (WIT)*, 2010.

[19] G. Bansal, H. Lu, J. B. Kenney, and C. Poellabauer, "Embarc: Error model based adaptive rate control for vehicle-to-vehicle communications," in *Proceeding of the tenth ACM international workshop on Vehicular inter-networking, systems, and applications*. ACM, 2013, pp. 41–50.

[20] M. Sepulcre, J. Gozalvez, O. Altintas, and H. Kremo, "Integration of congestion and awareness control in vehicular networks," *Ad Hoc Networks*, vol. 37, 2016.

[21] M. Sepulcre, J. Gozalvez, and M. C. Lucas-Estañ, "Power and packet rate control for vehicular networks in multi-application scenarios," *IEEE Transactions on Vehicular Technology*, 2019.

[22] M. I. Khan and J. Härri, "Integration challenges of facilities-layer DCC for heterogeneous V2X services," in *IV 2018, 29th IEEE Intelligent Vehicles Symposium, 26-29 June 2018*.

[23] G. Bansal and J. B. Kenney, "Achieving weighted-fairnessin message rate-based congestion control for dsrc systems," in *2013 IEEE 5th International Symposium on Wireless Vehicular Communications (WiVeC)*. IEEE, 2013, pp. 1–5.

[24] ETSI, "TS 102 687: Decentralized congestion control mechanisms for intelligent transport systems operating in the 5 ghz range, v1.1.1," 2011.

[25] "ETSI TR 101 612 intelligent transport systems (its); cross layer dcc management entity for operation in the its g5a and its g5b medium; report on cross layer dcc algorithms and performance evaluation," 2014.

[26] "iTETRIS project," http://wiki.ict-itetris.eu/index.php/Main_Page.

[27] L. Cheng, B. E. Henty, D. D. Stancil, F. Bai, and P. Mudalige, "Mobile vehicle-to-vehicle narrow-band channel measurement and characterization of the 5.9 ghz dedicated short range communication (dsrc) frequency band," *IEEE Journal on Selected Areas in Communications*, vol. 25, no. 8, pp. 1501–1516, 2007.

[28] H. C. Manual, "Highway capacity manual," *Washington, DC*, vol. 2, 2000.

[29] ETSI, "EN 302 637-2 v1.4.1-intelligent transport systems (its); vehicular communications; basic set of applications; part 2: Specification of cooperative awareness basic service," 2019.