In Vehicle Resource Orchestration for Multi-V2X Services

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***Abstract*—Transmit Rate Control (TRC) for V2X networks is critical for distributed channel resource allocation, limiting the channel usage per vehicle while preventing channel saturation. Similarly, efficiently distributing the limited transmit opportunities among multiple services of a vehicle is necessary, but has not been sufficiently studied. In this paper, we present a multi-V2X service resource orchestrator composed of two complementary mechanisms: (i) a multi-factor prioritization function, (ii) a budgetary scheduler allowing smooth resource earning/spending. Simulation-based evaluations showed improved access time for various V2X services under restricted resources and enhanced control on resource balancing between V2X services.**

I. Introduction

V2X communication will soon be ubiquitous in our roads to improve traffic safety and transport efficiency. The first and so far the major V2X service has been to increase a vehicle's awareness by communicating information beyond the driver's visual range and the vehicle's on-board sensors. Safety V2X messages such as Cooperative Awareness Messages (CAM) or Basic Safety Messages (BSM), V2X networking protocols and communication technologies have already been consolidated for initial, or DAY 1 deployments. In the future, revolutionary V2X applications, such as highly automated driving will be based on a multitude of V2X services (perception, CACC, HD-maps, etc..). This will require more robust communication mechanisms supporting such multiple V2X services.

Over the years, two leading wireless communication technologies have been developed for V2X communication: ITS-G5/DSRC based on IEEE 802.11p and 3GPP LTE-V2X. In 802.11 and LTE-V2X (Mode 4) based vehicular networks, there is no centralized channel resource orchestrator and each ITS station needs to prevent channel congestion by monitoring the channel activity and limiting its channel usage. Thus, decentralized channel congestion control protocols for both technologies have been standardized by SAE in the USA [1] and ETSI ITS in Europe [2]–[4], targeted mainly for a single V2X service and a single V2X message, i.e. CAM/BSM. Although differences exist between SAE/ETSI and between access technologies, these mechanisms have in common to involve at least a rate control via traffic shaping.

Although easy to implement, traffic shaping at the Access layer has drawbacks, as the OSI layering provides only limited knowledge of the V2X service requirements in the form of abstract 'Traffic Classes' (TC). Considering multi-V2X services, traffic shaping cannot differentiate between V2X messages using the same TC, and worse, strict prioritization among TCs leads to V2X service starvation. Considering that traffic shaping has the potential to drop or delay V2X messages beyond the V2X service validity, congestion control should be performed closely with V2X services.

This paper has the following contributions: i) illustration of the limitations of traffic shaping at the Access layer for multi-V2X safety services, ii) a multiple factor prioritization function introducing ranking, usefulness and urgency for fine grained resource balancing between V2X services; iii) a budgetary scheduler based on resource earning/spending supporting a smoother resource allocation over time. Altogether, our proposed resource orchestrator allows a flexible adjustments in time of the priority between V2X services as function of their dynamic budget.

The resource orchestrator is presented and analyzed on top of IEEE 802.11p based ITS-G5 Access technology, but can be extended to be compatible with other technologies as well. Similarly, the orchestrator's goal is not to perform a node's transmit rate control, but to distribute the transmission opportunities granted by the Access layer Transmit Rate Control among the various services of a node.

The rest of the paper is organized as follows: Section II presents a brief overview of related work, followed by Section III, which analyzes traffic shaping at the MAC layer. Section IV presents multi factor traffic prioritization and our proposed resource orchestrator at the Facilities layer. Section V illustrates performance evaluation results, and Section VI concludes the paper.

II. Related Work

Congestion control in V2X networks has been an active research topic for the past decade and several algorithms have been proposed and some have been standardized, by ETSI in Europe and by the SAE in the USA. The SAE channel congestion control adjusts the transmit rate and power considering multiple input parameters from lower layers, such as channel load, vehicular traffic density, packet error rate and neighbor tracking errors [1].

In Europe, wireless congestion control, commonly known as Decentralized Congestion Control (DCC), has been standardized by ETSI, to regulate the transmit rate using a traffic shaping 'gatekeeper' adjusting transmit parameters reactively to the channel load via a table lookup. The justification and values of these parameters were not initially well designed, leading such 'reactive' DCC to be ineffective [5].

The ETSI DCC has been recently revised [2] by including a linear adaptive approach based on Limeric [6]. As an alternative to the reactive DCC, such an 'adaptive' DCC adjusts the transmit rate according to a target channel load. The adaptive method has been shown to function better than the reactive approach, as presented in [7].

On the research side, wireless congestion control has been investigated by distributively controlling a node's transmit rate [6], transmit power [8], or both [9], while ensuring a smooth rate convergence, stability and fairness in the control process [10]. However, managing multiple services generating different types of messages with different transmit patterns

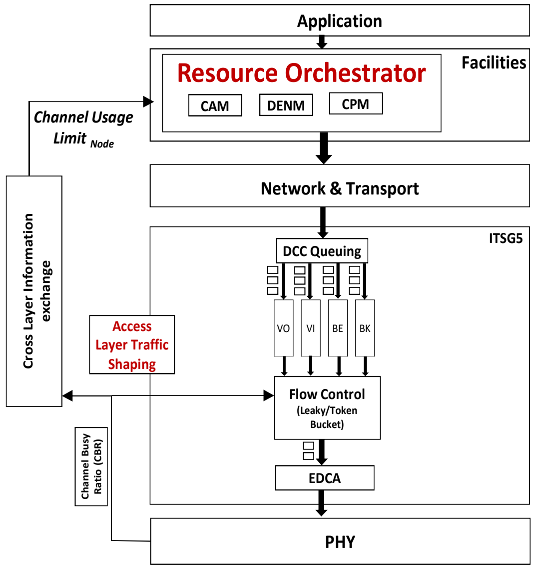


Figure 1: Congestion Control Stack Diagram

(broadcast or unicast, periodic or triggered), has not received much attention so far.

Several studies analyzed multiple V2X applications [11], [12], yet depending on a single service and transmitting a single message, i.e. CAM/BSM. Recent studies [13]–[15] investigated the performance of congestion control protocols considering multiple messages, showing the starvation of lower priority services under channel congestion. In order to mitigate such starvation, our previous work [16] proposed a resource management approach dynamically regulating the packet generation delay between services. In this work, we propose a much more general approach, including a multi-factor priority function and a budget scheduler for a more granular resource balancing between V2X services/applications.

III. Access Layer Traffic Shaping

In IEEE 802.11p based vehicular networks, each node decentrally monitors the channel load and calculates its channel occupancy limit, enforced via traffic shaping at the Access layer. It uses Absolute Priority FIFO mechanism for queuing, and Leaky Bucket for flow control, as shown in Fig 1. However, such traffic shaping philosophy is subject to several limitations.

A. Issues with Access Layer Traffic Shaping

Packet Starvation: Absolute priority queuing may indefinitely starve packets in a low priority queue during channel congestion, when a node's channel occupancy limit is insufficient to satisfy all the priorities.

Access Layer limited knowledge: At the Access layer DCC queues, there is no notion of service or application, but only Access Category (AC). If two messages, such as CAM and Cooperative Perception Message (CPM) belong to the same AC, it cannot provide differentiated QoS between CAM and CPM.

Coordination between Applications and Flow Control: The DCC at access layer allows a coordination with V2X services message generation at Facilities layer in order not to generate packets when no transmission opportunities exist. However, V2X services should not only coordinate with the Access layer flow control, but also among themselves to arbitrate the usage of the next transmission opportunity.

B. Need for a Resource Orchestrator

Due to the limited knowledge and degree of freedom at the Access layer, limited QoS options leading to hard decisions and the lack of coordination between V2X services, an multi-V2X service orchestrator located at the Facilities layer would be more efficient. The design guideline of such orchestrator should be: 1) located at Facilities to allow a tight coordination between V2X services, 2) receive the transmit opportunities from the Access layer and orchestrate their usage between V2X services, 3) provide extended QoS levels to integrate application-level requirements on V2X services, 4) avoid service starvation of lower V2x services through dynamic QoS reallocation.

An extension of DCC is being standardized[1] as Communication Congestion Control [17], to supplement Access DCC with packet generation control at the Facilities layer. However, the proposed design follows the absolute prioritization of one TC over another, and has issues discussed in [16]. Similarly, distributing the rate control decision across Access and Facilities layers without proper coordination can lead to incompatibility and conflicting decision, as shown in [15].

IV. Facilities Layer Resource Orchestrator

In this section, we outline our proposed mechanism to: i) allocate resources for V2X services based on dynamic parameters, and ii) schedule the service's next packet based on the allocated resource, while harmoniously synchronizing with the Access DCC down below, which is conceptually shown by the block diagram in Fig 2.

A. Service Characterization

Instead of using static TCs, we propose to characterize each service using 3 properties to calculate its share of a node's total transmission opportunity:

- **Rank [0-1]:** primary differentiator to differentiate between services of different priority. Without loss of generalities, a typical rank could take four values [1, 0.75, 0.5, 0.25, 0] to match the 4 EDCA AC.
- **Usefulness [0-1]:** measures how useful is the message in the context. A message 'usefulness' is established either as function of neighbors requesting it, or having been sending it as well; for example, if CAM is useful for 100% of the neighbors its usefulness will be 1, and if only 50% of neighbors will benefit from a CPM, it will be 0.5.
- **Urgency [0-1]:** A message urgency is proportional to the remaining time before a deadline set by a V2X service.

Thus, a Multi Factor Priority ($MFP_{service_i}$), is a weighted sum of:

$$MFP_{service_i} = \alpha_1 Rank + \alpha_2 Usefulness + \alpha_3 Urgency \tag{1}$$

Considering a node has 3 applications or services[2], DENM, CAM and CPM. DENM has a Rank of 0.75, CAM 0.5 and CPM 0.25. For simplicity, let the weight of each factor be 1 and DENM is always urgent with urgency value 1, and the other two services are not urgent with urgency value 0. Let

[1] still as a draft, at the time of writing

[2] in this paper we don't differentiate between application and service, so use the words interchangeably

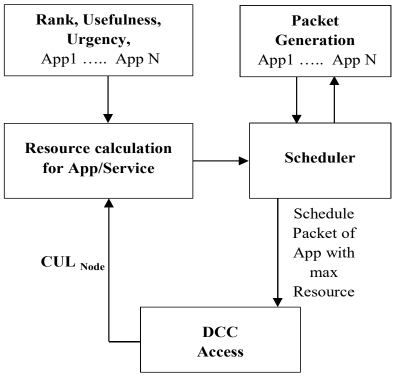


Figure 2: Resource Orchestration Block Diagram

the usefulness value be 1 for all the services. Then the MFP values will be: DENM: 0.75 + 1 + 1 = 2.75, CAM: 0.5 + 1 + 0 = 1.5 and CPM: 0.25 + 1 + 0 = 1.25. A resource share R_i for each service is proportional to its MFP as:

$$R_i = \frac{MFP_{service_i}}{\sum_k MFP_{service_k}} \tag{2}$$

Thus in the above example, DENM will have 2.75÷5.5 = 50% of channel resources, CAM will have 1.5÷5.5 = 27% and CPM will have the rest 23% of channel resources.

B. *Resource Orchestration among Services*

As mentioned earlier, the Access DCC can be reactive or Adaptive as in [2]. The Reactive approach has been shown to have compatibility issues with the Facilities layer [15], so is not considered here. The Adaptive approach sets the node's Channel Usage Limit (CUL) [3], which is compatible with the Facilities layer. The CUL is a unitless value provided by the Access DCC mechanism [2]. It is also the maximum fraction of time a node is allowed to transmit on the channel.

$$CUL_{Node} = \frac{T_{on_{Node}}}{T_{on_{Node}} + T_{off_{Node}}} \tag{3}$$

T_{on} is the duration of a transmission, while T_{off} is the duration of non-transmission. $\mathrm{CUL_{Node}}$ can be divided into CUL per application or service (i) as:

$$\begin{aligned} CUL_{Node} &= \sum_i CUL_{Node} * R_i = \sum_i CUL_i \\ &= \sum_i \frac{Ton_i}{Ton_i + Toff_i} \end{aligned} \tag{4}$$

The $\mathrm{CUL_i}$ is considered as the resource for service i, which depends on its share $\mathrm{R_i}$. At any time, the net resource $\mathrm{N_i(t)}$ of a service depends on the remaining resource after last transmission $\mathrm{N_i(t\text{-}1)}$ plus an accumulated resource $\mathrm{A_i(\Delta t)}$. $\mathrm{A_i(\Delta t)}$ is directly proportional to the time since last transmission Δt, and also depends on the packet air-time $\mathrm{T_{on}(t\text{-}1)}$ of last Tx and the corresponding $\mathrm{T_{off}(t\text{-}1)}$. It is given by:

$$\begin{aligned} N_i(t) &= N_i(t-1) + A_i(\Delta t) \\ &= N_i(t-1) + \frac{\Delta t}{Ton_i(t-1) + Toff_i(t-1)} \\ &= N_i(t-1) + \frac{\Delta t}{Ton_i(t-1)} * CUL_i \\ &= N_i(t-1) + \frac{\Delta t}{Ton_i(t-1)} * \ R_i * CUL_{Node} \end{aligned} \tag{5}$$

[3]CUL is analogous to the parameter δ in ETSI TS 102 687 [2]

Table I: Resource Orchestration Example

Current time (ms)	DENM	CAM	CPM	Packet Tx	DCC Access next TxOp at time (ms)
	Resource				
0	0.5	0.3	0.4	-	
100	1	0.6	0.8	DENM	200
200	0.5	0.9	1.2	CPM	250
250	0.75	1.05	0.4	CAM	350
350	1.25	0.35	0.8	DENM	450
351	0.25	0.35	0.8	-	450
450	0.75	0.65	1.2	CPM	500
500	1	0.8	0.4	DENM	600
600	0.5	1.1	0.8	CAM	700
700	1	0.4	1.2	CPM	750
750	1.25	0.55	0.4	DENM	850
850	0.75	0.85	0.8	CAM	950
950	1.25	0.15	1.2	DENM	1050
1050	0.75	0.45	1.6	CPM	1100

Whenever the next transmit opportunity is allowed by the Access DCC, the accumulated resource of each service is calculated and the service with the highest resource is allowed to transmit by the orchestration, as shown in Fig 2. Each transmission costs a resource $\mathrm{C_i(t)}$ to the service, based on the packet's air time, $\mathrm{Ton}_i\mathrm{(t)}$, and is the new $\mathrm{N_i(t)}$ is obtained as :

$$\begin{aligned} N_i(t) &= N_i(t-1) + A_i(\Delta t) - C_i(t) \\ &= N_i(t-1) + A_i(\Delta t) - \frac{Ton_i(t) * (1 - CUL_i)}{Toff_i(t-1) * CUL_i} \end{aligned} \tag{6}$$

Considering a node can use 0.4% of channel resource, so its CUL_{Node} will be 0.004. It gives 50% to DENM, i.e. 0.002, 30% to CAM and 20% to CPM. The packet size of CAM and DENM is 300 Bytes in this example, with Ton_{CAM} and Ton_{DENM} of 0.0004 sec, and packet size of CPM is 150 Bytes, Ton_{CPM} is 0.0002 sec, considering 6Mbps data rate. Then according to the above resource orchestration mechanism, the orchestration will be, as shown in Table I.

The first column shows the current time, followed by the resource of each service at that time. The 4th column shows the packet transmitted from the service having earned the biggest resource. The last column shows the earliest time when Access DCC will allow the next packet transmission after the *Toff* period.

As time passes each service earns resources as in Eq.5, which are spent during packet transmissions as in Eq.6. In Table I, at 350ms DENM service has a resource of 1.25, higher than CAM and CPM, so the orchestrator allows a DENM. Using Ton_{DENM}, $Toff_{DENM}$ and CUL_{DENM} values, its resource at 351ms, after transmission is calculated by Eq. 6 as: 0 + 1.25 - (0.0004*(1-0.002))/(0.2*0.002) = 0.25. Similarly, at 450ms, 100ms (0.1 sec) after its last Tx, its resource is calculated by Eq. 5 as: 0.25 + 0.1/0.0004 * 0.5 * 0.004 = 0.75. Similarly, at 500ms, its resource is 1, higher than the two other services and a DENM is again sent.

V. Performance Evaluation

In this section, we present simulation based evaluation results to demonstrate the benefit of resource orchestration at the Facilities layer. Moreover, we analyze why a simple static traffic prioritization is non optimal for traffic scheduling and how considering multiple factors can optimally serve all the packet types.

A 4 by 4 lane sub-urban highway is simulated with vehicles moving between 70 to 90kmh following a Gauss-Markov mobility, for various levels of traffic density, up to 50 vehicle/lane/km, corresponding to Level of Service F of the highway capacity manual [18]. The iTETRIS [19] simulator is used, which includes the ETSI ITS stack an the adaptive access DCC. The wireless channel is modeled according to

WINNER B1 model, having Gaussian Shadowing & Ricean fast fading.

Each node runs 3 safety applications CAM, DENM and CPM. CAM packets are generated using the triggering conditions stated in ETSI EN 302 637-2. CPMs are emitted at an uniform random rate of 1-5 Hz. The max and min rates are stated in ETSI TS 103 324, while the exact triggering conditions are still being standardized and not simulated here. Lastly around 10% of the vehicles emit a single burst of 100 DENMs, at a rate of 10Hz. In this simulation, DENMs are not forwarded and simulating exact DENM emission conditions is out of the scope of this paper. Nevertheless, DENM or any geonet packet forwarding can be treated just as another service by the resource orchestrator and will be analyzed in future work. The performance is evaluated in terms of DCC queue delay, Requested vs Allowed transmit rate and channel load. Table II summarizes the main simulation parameters.

A. *Access DCC Queue Delay: need for Facilities Scheduler*

Figure 3 shows the DCC Queue Delay for various levels of traffic density, for CAM and CPM packets using DCC Access alone and accompanied by Communication Congestion Control [17] at the Facilities layer using static Traffic Class. In the rest of the paper, it will be referred to as Facilities Layer Congestion Control (FLCC).

Without FLCC, the packet triggering mechanism checks the interval between packet generation (IBPG) w.r.t congestion level indicated by parameters such as *T_GenCam_DCC* (EN 102 637) or *T_GenCpm_DCC*[4]. For a given channel load a lower traffic priority has a higher IBPG as stated in ETSI TS 102 724. However, in this simulation both CAM and CPM have the same IBPG values w.r.t channel load, as according to the limits set by TS 102 724, IBPG values for a priority level lower than CAM never allows a transmit rate of 5Hz (the maximum for CPM), regardless of the channel load.

Although, the values *T_GenCam_DCC* and *T_GenCpm_DCC* coordinate the packet generation of each service with the Access DCC, but without coordination between the services, a service is unaware whether another service will use the next transmit opportunity. Thus, two services waiting for the next transmit opportunity, can generate a packet, while only one packet will get transmitted and the other will be queued in the DCC queues. As can be seen in Fig 3, for high node densities, CAMs get delayed by 80ms, while CPMs by 120ms for Reactive DCC, while both packets by 50ms for Adaptive DCC. Reactive DCC performs worse than Adaptive DCC, as showed by previous studies [7], [15].

However, when FLCC coordinates the packet generation between the services in cooperation with the Access DCC, there is no DCC Queue Delay, either for Adaptive or Reactive DCC. This shows the necessity of a Facilities layer scheduler, instead of each service itself regulating the packet generation using *T_GenCam_DCC* or *T_GenCpm_DCC*. Nevertheless, even if FLCC can prevent DCC queuing delay, using static TC can be problematic, during channel resource scarcity, which is analyzed in the next sub section.

Table II: Simulation Parameters

Parameter	Value
Transmit Rate	CAM triggered, CPM 1-5 [Hz] DENM 10 [Hz]
Transmit Power	23 dBm
DataRate	6 Mbps
Packet Size	CAM 300 Bytes, CPM 650 Bytes DENM 400 Bytes
Packet Priority	DENM: (VI), CAM (BE), CPM (BK)
Mobility	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	WINNER B1 Urban Microcell (Correlated Gaussian & Ricean)
Preamble DetectionThreshold	- 92 dBm
Performance Indicators	Queue Delay, Inter Transmit Time, Channel Load Avg 50 runs

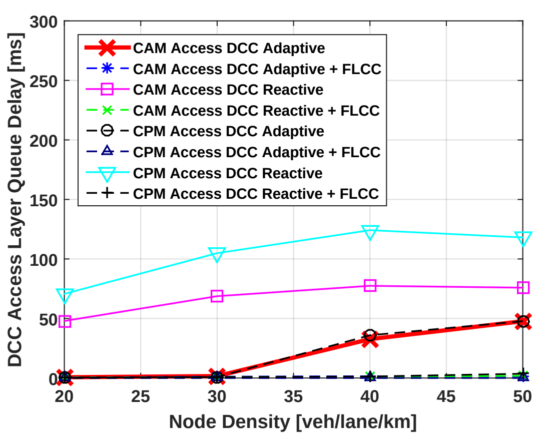


Figure 3: Access DCC Queue Delay, with and without Facilities Layer Congestion Control

B. *Facilities Layer Scheduler: Packet Prioritization*

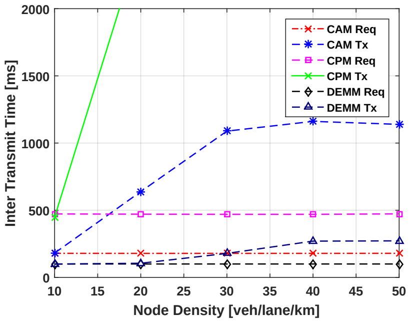
In this subsection, we analyze the performance using 3 services, DENM, CAM and CPM, with EDCA AC Video, Best Effort and Background. Instead of each service individually coordinating IBPG with Access DCC via parameters such as *T_GenCam_DCC* or *T_GenCpm_DCC*, each node uses FLCC with static TC to arbitrate the packet generation opportunities among the services. Although FLCC, is yet to be finalized in the standards[5], for performance evaluation in this paper, we use its design philosophy of resource allocation to each service using static TC. We compare the scheduling performance using static TC versus the Multi Factor Priority (MFP) as discussed in Section IV.

Figure 4a shows the difference in the Inter Transmit Time (ITT) asked by each service and allowed by FLCC using static TC. On average, DENM requests 100ms ITT, CAM 200ms and CPM around 500ms ITT. However, as the node density or channel load increases, the ITT increases. Above a density of 30veh/lane/km (channel load 70%), the CPM ITT exceeds 3 seconds, and CAM over 1 second, while allocating 150 to 250 ms ITT to DENM. As described earlier, static prioritization is fixed and cannot be modified by FLCC, highly degrading the performance of lower TCs.

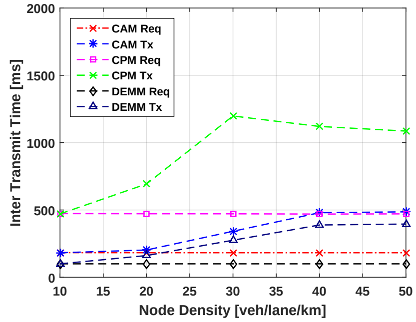
However, using the MFP the scheduler has much more flexibility to allocate resource among the services. Figure 4b shows the ITT when each service DENM, CAM and CPM are given 50%, 27% and 23% priority using the priority values of 2.75 for DENM, 1.5 for CAM and 1.25 for CPM as in the example of Section IVa. The ITT of CPM and CAM are much better than static prioritization. However, this comes at a cost

[4] CPM triggering conditions w.r.t DCC haven't been finalized yet, here it is expected to be similar to CAM, i.e. using *T_GenCpm_DCC*

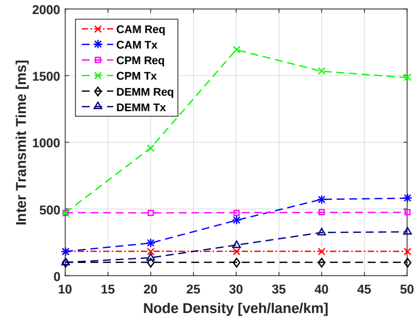
[5] [17] is still a draft



(a)



(b)



(c)

Figure 4: Inter Transmission Time (a) Static Traffic Prioritization (b) Multi Factor Priority (MFP) Scheduler (c) MFP Scheduler with more resource for DENM

of as much as 150ms performance degradation of DENM at higher channel loads.

Therefore, if the DENM performance is inadequate, then the resource calculation functionality can reduce the priority factors of CAM and CPM to give a higher resource share to DENM, using Eq. 1 & 2. Thus, Figure 4c shows the reduction in DENM ITT by around 100ms, when 60% resource share is allocated to DENM, while CAM and CPM having a reduced share of 25% and 15% respectively.

Both the mechanisms, i.e. static and MFP produce similar loads, as in Fig 5. The load increases gradually till 70%, after which it converges between 70 to 75%. In fact, limiting the channel load is the role of the Access DCC, and the Adaptive DCC used here, performs the job well. The role of the presented scheduler is to take the limit of the Access DCC and manage the transmit opportunity among the applications. Therefore, whether allocating 50% or 60% share to DENMs, doesn't change the channel load.

VI. Conclusion

In this paper, we presented a multi-V2X service orchestrator supporting resource balancing between various V2X services under constrained channel usage, and functioning in coordination with the ETSI Adaptive Access DCC. The orchestrator's multifactor priority function provides a fine grained control between rank, usefulness and urgency of V2X services, accompanied by a budget scheduler which allows a smoother resource usage over time. Altogether, the allocated resources vary between V2X services adapting to resource constraints without starving any of them. Although we tested it with ETSI Adaptive Access DCC and IEEE 802.11p based ITS-G5 access technology, in future work we plan to test it on top of other technologies.

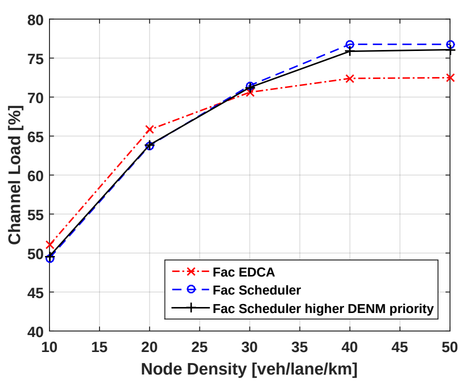


Figure 5: Channel Load

Acknowledgment

EURECOM acknowledges the support of its industrial members, namely, BMW Group, IABG, Monaco Telecom, Orange, SAP and Symantec. The authors acknowledge the partial financial support of Renault SAS.

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