Adapting the Resource Reservation Interval for Improved Congestion Control in NR-V2X

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***Abstract*—This paper presents a detailed quantitative evaluation of standardised ETSI & 3GPP Decentralised Congestion Control (DCC) and packet dropping mechanisms for Cellular V2X (C-V2X) and New Radio (NR) V2X. Based on the identified shortcomings, an Access layer scheme, *RRI DCC*, is then proposed. *RRI DCC* explicitly accommodates the sidelink scheduling mechanism Sensing Based Semi-Persistent Scheduling (SB-SPS), eliminating incompatibilities between current standards and the scheduling mechanism, to avoid unnecessary and recurring collisions. Three variants are proposed; one is an evolution of the ETSI Reactive DCC mechanism, the second is based on the ETSI Adaptive DCC mechanism and the final aligns with the 3GPP approach based on channel occupancy ratio (CR). All approaches are compared with current ETSI and 3GPP standards and exhibit improved performance. An evaluation of the proposed *RRI DCC* mechanisms and existing DCC standards, to meet the Quality of Service (QoS) requirements of vehicular cooperative awareness applications is also conducted.**

***Index Terms*—Cellular V2X, New Radio NR-V2X, LTE-V, sidelink, congestion control, Mode 4, Mode 2, packet dropping, SB-SPS.**

I. Introduction

Cooperative awareness between vehicles (V2V) or between vehicles and infrastructure (V2I) forms the basis for future envisaged vehicular communication services. There are currently two communication technologies i.e. the well studied and mature IEEE 802.11p (ITS-G5 in Europe) or the emerging equivalent known as Cellular Vehicle-to-Everything (C-V2X). The 3rd Generation Partnership Project (3GPP) defines two variations, namely LTE-V (Release 14) [1] often referred to as C-V2X and New Radio (NR) V2X (Release 16) [2]. In Mode 3 (scheduled), the cellular base station allocates and manages the resources necessary for V2V sidelink (PC5) communications. In Mode 4 (autonomous) each vehicle selects its radio resources for V2V communications using the distributed scheduling algorithm, Sensing Based Semi-Persistent Scheduling (SB-SPS) [3]. Mode 4 represents the baseline performance for C-V2X. The equivalent in NR-V2X is Mode 1 for scheduled and Mode 2 for autonomous resource selection which uses an adapted form of the SB-SPS algorithm.

Irrespective of whether wireless or cellular V2X technology is employed, both standards will be required to handle a congested radio environment due to limited spectrum, widespread vehicular deployment and frequent packet exchange. As such, congestion control techniques are hugely important for managing channel load and radio interference. Decentralised Congestion Control (DCC) mechanisms as defined by the European Telecommunications Standards Institute (ETSI) have been well studied over the past decade for ITS-G5 [4]–[6] but have not been adequately investigated for NR-V2X or C-V2X. The operation of the NR-V2X MAC differs significantly from that of ITS-G5, particularly with respect to MAC layer scheduling. SB-SPS assumes packets arrive periodically and bases its resource reservation algorithm on this assumption. However, if packets arrive aperiodically in accordance with the ETSI CAM (Cooperative Awareness Message) generation rules or due to some congestion control mechanism based on transmission rate control (TRC), this can lead to prohibitively high packet collisions [7]. Furthermore, as SB-SPS maintains resources for a defined period known as a grant, these collisions may reoccur over the duration of the grant. Some initial studies [8], [9] have investigated the application of packet dropping for SB-SPS but to the author's knowledge no study explicitly evaluates all ETSI and 3GPP DCC and packet dropping congestion control standards applied to C-V2X and NR-V2X, as per this study.

Furthermore, to address the identified shortcomings of standardised approaches, this paper proposes DCC mechanisms that are compliant with the SB-SPS algorithm and address the problem of excessive collisions due to the perception of unused yet reserved resources as well as continuous grant rescheduling. This is achieved by adapting the resource reservation interval (RRI) within the SB-SPS grant in line with measured Channel Busy Ratio (CBR) as per the ETSI DCC mechanism or 3GPP channel occupancy. This approach drastically reduces the collisions by ensuring that resource usage is more predictable and does not result in recurring collisions within an SB-SPS grant, while maintaining the grant for longer. This eliminates the shortcomings of existing congestion control approaches when directly applied to SB-SPS.

It is also important to recognise that while congestion control mechanisms may improve radio conditions and in turn the measured packet delivery rates, it may not improve the performance achieved at the application layer. If a high number of application layer or cooperative awareness packets are delayed or dropped this may render the service unsafe or unusable. As such, it is of the utmost importance to consider the impact of DCC on the upper layer applications Quality of Service (QoS) requirements.

The rest of this paper is organised as follows: Section II gives an overview of standardised ETSI and 3GPP DCC approaches as well as state of the art DCC research. As many acronyms are used in this paper, an explanatory table is provided in Table I. The proposed *RRI DCC* congestion control mechanisms that account for the NR-V2X MAC layer are described in Section III. Section IV quantitatively evaluates the limitations of existing DCC standards, with Section V discussing the performance of *RRI DCC* to address said limitations. Sections VI and VII provide a discussion on outstanding research questions and concluding remarks.

TABLE I: Abbreviations/Acronyms used in this study.

Acronym	**Description**
	Standards
ITS-G5	European ETSI wireless standard for vehicular communications (based on 802.11p).
LTE-V/C-V2X	3GPP Release 14 standard for vehicular communications (based on LTE).
NR-V2X	3GPP Release 16 standard for vehicular communications.
SB-SPS	Sensing Based Semi-Persistent Scheduling (uses a grant mechanism).
DCC Reactive	ETSI Decentralised Congestion Control based on transmission rate control (TRC) look up table.
DCC Adaptive	ETSI Decentralised Congestion Control based on transmission rate control (TRC) algorithm. The algorithm is based on LIMERIC.
LIMERIC	Linear Adaptive Message Rate Algorithm.
	Scheduling
SCI	Sidelink Control Information.
CSR	Candidate single Subframe Resource. Can be one or more subchannel.
RRI	Resource Reservation Interval. Period between transmissions.
GB / No GB	SB-SPS Grant Breaking parameter. Defines whether a subchannel is maintained or not.
	Metrics
PDR	Packet Delivery Rate.
CBR	Channel Busy Ratio, measure of channel congestion.
CR	Channel occupancy Ratio, measure of channel usage for individual vehicles.

II. Congestion Control Standards for Vehicular Communications

Wireless (ITS-G5) and cellular vehicular communication standards (C-V2X & NR-V2X) either define the channel conditions under which congestion control mechanisms should be employed and/or the congestion control mechanism itself. DCC mechanisms can broadly be categorised as follows:

- Transmission Rate Control (TRC):
  (a) Delay packet transmission: packets are delayed/queued to reduce channel load.
  (b) Drop packet transmission: packets are simply dropped to reduce channel load.
  (c) Retransmission reduction: packet retransmissions are eliminated or reduced in high congestion scenarios.
- Modulation & Coding Scheme (MCS) Adaptation: Use of higher order MCS' to reduce channel congestion at the cost of a less robust transmission.
- Transmission Power Control (TPC): Reducing transmission power to reduce communication range and thereby channel congestion.

While ETSI specifies TRC congestion control mechanisms for ITS-G5, neither ETSI or 3GPP specify such mechanisms for C-V2X or NR-V2X. Instead only the channel conditions under which congestion control mechanisms may be invoked are specified. A summary of the relevant features of existing congestion control standards is now provided.

A. ETSI ITS-G5 Decentralised Congestion Control (DCC)

ETSI defines the most mature detailed set of vehicular DCC mechanisms in [10], originally developed for ITS-G5. The defacto mechanism is transmission rate control which works by increasing the delay between packet transmissions based on the CBR. The means by which this delay is determined is how ETSI distinguishes between its two TRC mechanisms, namely DCC Reactive and DCC Adaptive.

DCC Reactive is the original approach specified by ETSI based on a state machine, whereby a state is associated with a particular CBR range. Depending on the CBR, a delay is introduced between consecutive packets to control the transmission rate. This is shown in Table II. The maximum allowed transmission rate for a CBR range is enforced using T_{off}, the time period before a new consecutive packet can be transmitted. DCC Adaptive is a rate control mechanism based on the LIMERIC algorithm [4]. Rather than using a predefined lookup table, its algorithm adjusts the packet rate transmission to converge on a target CBR, with a default of 68%. DCC Adaptive better considers factors such as stability and fairness to ensure no node is starved. Amador et al. provide a detailed analysis of ETSI DCC Adaptive for ITS-G5 in [11].

TABLE II: ETSI ITS-G5 Reactive DCC as specified in [10].

CBR	**State**	**Packet Rate**	$\mathbf{T_{off}}$
$CBR < 0.3$	Relaxed	10Hz	100ms
$0.3 \leq CBR \leq 0.40$	Active 1	5Hz	200ms
$0.40 \leq CBR \leq 0.50$	Active 2	2.5Hz	400ms
$0.50 \leq CBR \leq 0.60$	Active 3	2Hz	500ms
$CBR > 0.60$	Restrictive	1Hz	1000ms

TABLE III: ETSI V2X Congestion Control - Maximum CR limit per CBR range and packet priority [12].

CBR	**Priority 1-2**	**Priority 3-5**	**Priority 6-8**
$0 \leq CBR \leq 0.3$	no limit	no limit	no limit
$0.3 < CBR \leq 0.65$	no limit	0.03	0.02
$0.65 < CBR \leq 0.8$	0.02	0.006	0.004
$0.8 < CBR \leq 1$	0.02	0.003	0.002

TABLE IV: 3GPP V2X Congestion Control - Maximum CR limit per CBR range and packet priority [13].

CBR	CR limit
CBR $\leq$ 0.65	no limit
0.65 $<$ CBR $\leq$ 0.675	1.6e-3
0.675 $<$ CBR $\leq$ 0.7	1.5e-3
0.7 $<$ CBR $\leq$ 0.725	1.4e-3
0.725 $<$ CBR $\leq$ 0.75	1.3e-3
0.75 $<$ CBR $\leq$ 0.775	1.2e-3
0.8 $<$ CBR $\leq$ 0.825	1.1e-3
0.825 $<$ CBR $\leq$ 0.85	1.1e-3
0.85 $<$ CBR $\leq$ 0.875	1.0e-3
0.875 $<$ CBR	0.8e-3

B. C-V2X & NR-V2X Congestion Control - ETSI

In recent years, ETSI have set out some details relating to congestion control for C-V2X and NR-V2X [12]. Specifically, they describe how CBR and Channel Occupancy Ratio (CR) are to be measured. CBR provides an estimation of the overall channel congestion by measuring the ratio of subchannels over the last 100 subframes where the sidelink RSSI (S-RSSI) exceeds a predefined threshold. The CR measures the number of subchannels used by each vehicle over a historical time period as well as the subchannels that will be used based on the current configured grant. In Table III, ETSI specifies the maximum CR limit for each vehicle based on the measured CBR. If the measured CR exceeds the limit for the current CBR range, the vehicle must reduce its CR using a particular congestion control mechanism. ETSI highlights that this can include packet dropping, adaptation of MCS, or power control but do not specify precise implementations.

C. C-V2X & NR-V2X Congestion Control - 3GPP

The 3GPP standards for C-V2X and NR-V2X also do not provide a specific congestion control mechanism. However, similarly to ETSI, a 3GPP working group have defined the CBR and CR measurements under which it should be invoked, as shown in Table IV. This definition is more reactive than ETSI in terms of adjusting the CR limit when congestion occurs, however CBR thresholds are set much higher than the ETSI equivalent so congestion control is only employed when the CBR exceeds 65%. For the remainder of this paper we assume packet dropping is the congestion control mechanism invoked by this table.

D. Literature Review

One of the initial works to evaluate the impact of packet dropping for C-V2X (Rel. 14) is by Mansouri et al. [14]. It evaluates the performance of packet dropping based on the 3GPP C-V2X CR limits as per Table IV. This paper highlights some of the issues further discussed in Section V-A where vehicles mistakenly choose the same channel resources. The most similar work to the approach proposed in this paper is a reservation splitting technique by Wendland et al. [9]. The authors split a single SB-SPS grant into multiple sub-grants of lower frequency (e.g. 10Hz $\rightarrow$ 2 x 5Hz) and when the network is congested, individual sub-grants can be disabled without interrupting the SB-SPS grant mechanism. This approach is analogous to the proposed *RRI DCC* mechanism in that turning off a grant is similar to changing the RRI i.e. a single 5hz grant is the same as a grant with an increased RRI of 200ms. They compare their scheme against ETSI C-V2X DCC as per Table III. While the reservation splitting approach reduces recurring collisions within a single grant, it does not support dynamically re-enabling grants as congestion changes. In contrast, the proposed *RRI DCC* approaches allow this to occur and work within the existing SB-SPS mechanism without requiring any changes.

Sepulcre et al. [15] recently investigated the efficacy of packet dropping to meet application QoS requirements as a congestion control mechanism for ITS-G5. The authors show that application Packet Delivery Ratio (PDR) is impacted by packet dropping and performs worse than if no congestion control was applied despite improvements in radio performance. However, it is our premise that packet dropping can form part of a congestion control solution for NR-V2X as seen from results in Fig 8b and Table VII, where we observe similar IPG and increased neighbour awareness. This also highlights a need for further investigation into whether the transmission frequency of CAMs and other cooperative awareness services can be reduced such that they are only transmitted when meaningful and without impacting the awareness of vehicles. A similar premise was recently discussed by Bazzi et al. [16].

Other approaches look at combining mechanisms such as rate control, power control and MCS adaptation. The most prevalent of these is the North American Society of Automotive Engineers (SAE) DCC mechanism [17] that uses power and rate control. The rate control algorithm is derived from the LIMERIC algorithm [4] and power control is based on the Stateful Utilization- based Power Adaptation (SUPRA) which is designed to control communication range [18]. Research in [19]–[22] investigate the performance of the SAE standard for congestion control. Generally, these authors have shown performance increases over standard rate control while showing minor improvements from power control, with the need for further study before determining their effectiveness for C-V2X and NR-V2X.

Notably, all the mechanisms described thus far are access layer approaches. Such mechanisms have limitations when simultaneously considering multiple application layer services with different QoS requirements. As such, ETSI has begun to define the Facilities layer DCC which coordinates between Access layer congestion control mechanisms and higher layer services. It can also operate as a standalone mechanism without lower layers. The goal is to ensure that nodes can predict available resources and more intelligently distribute channel resources across the services that they are tasked with fulfilling. ETSI has not yet standardised Facilities layer DCC but some works [11], [23]–[25] have investigated possible implications and implementations.

III. Resource Reservation Interval Decentralised Congestion Control (RRI DCC)

In Section IV, the results in this paper will show that traditional TRC mechanisms like DCC or packet dropping are incompatible with the C-V2X and NR-V2X SB-SPS mechanisms when a scheduled transmission is missed, leading to unnecessary collisions. The reason for this is illustrated in Fig 1. In timeline (A), no missed transmission occurs i.e. an application layer packet is always available to send in the scheduled slot. As such, all the transmitted packets, shown in blue, transmit an SCI message providing an RRI which indicates planned use of future resources. These resources are then excluded for selection in the sensing window of other vehicles. Timeline (B) shows the issue when a missed transmission occurs i.e. an application packet does not exist to send in a scheduled slot. This can be due to either a delay or a packet drop as a result of a congestion control mechanism and is shown in red, with MT signifying the missed transmission opportunity. As a result, no SCI is transmitted, resulting in neighbouring vehicles considering the resource to be free in the future when it may yet be used for subsequent transmission, especially if grant breaking is disabled. This highlights the need for any proposed congestion control approach to consider the underlying scheduling mechanism, explicitly taking the SB-SPS Resource Reservation Interval (RRI) into account.

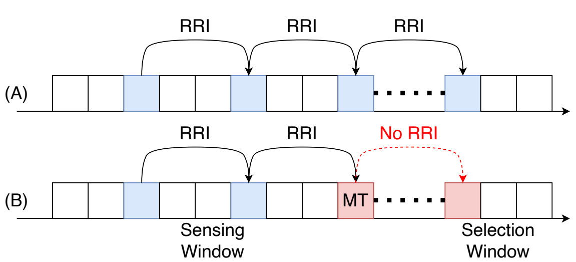


Fig. 1: SB-SPS missed transmission impact.

To address this, three *RRI DCC* mechanisms are proposed. These mechanisms adjust the time between transmissions based on the current CBR measurement, while considering the RRI of the SB-SPS grant. Three variants are proposed to align with existing vehicular congestion control standards as set out in Section II, specifically to align with ETSI DCC Reactive, ETSI DCC Adaptive and packet dropping with 3GPP CR limit tables. They operate as follows:

- **$\text{RRI}_{\text{Reactive}}$**: DCC Reactive uses a lookup table to determine the packet delay i.e. T_{off} parameter, based on the measured CBR. This results in a packet delay that may not be compatible with the SB-SPS RRI i.e. reserved transmission slots. However $\text{RRI}_{\text{Reactive}}$ ensures that the delay offset is linked to a multiple of the default RRI, preventing grant breaks and unused resources. Furthermore an SCI is broadcast indicating the new RRI to neighbouring vehicles. This controls the rate of packet transmission without missing a scheduled slot.
- **$\text{RRI}_{\text{Adaptive}}$**: This approach uses the ETSI defined DCC Adaptive algorithm to determine the packet delay i.e. T_{off} [10]. In the standard, six equations are used to calculate the proportion of the channel that the vehicle is allowed to use, based on previous usage and current CBR. These can be translated for NR-V2X due to the equivalent nature of CBR calculation for ITS-G5 and NR-V2X i.e. calculating CBR based on sub-channel usage vs time sensed as busy. For the channel usage or δ parameter, instead of calculating a proportion of time spent transmitting, as is the case in ITS-G5, we substitute the calculated CR. However as the use of the 3GPP calculated CR is a combination of future and historical usage, this causes CBR oscillations hindering convergence on a target CBR. Hence only historical CR is used. The most significant change is translating equation B.1 in [10], to calculate the final T_{off} parameter. Equation 1 shows how δ is used to calculate the delay T_{off}. We calculate S_{used} as the number of subchannels used in the previous transmission and S_{total} is the total number of subchannels per subframe for the previous second. As it must be ensured that the generated T_{off} time corresponds to a multiple of the default RRI, equation 2 provides this translation. Importantly, there is no means to update the RRI after its transmission in the SCI and as such no means of using an adapted version of equation B.2 in the standard.

$$T_{\text{off}} = ((S_{\text{used}}/S_{\text{total}} * 1000)/\delta) * 1000 \tag{1}$$

$$rri = round(max(100, min(T_{\text{off}}, 1000)) \tag{2}$$

- **$\text{RRI}_{\text{CR\_limit}}$**: This approach is based on packet dropping to reduce an individual vehicles' CR-limit. Similar to the ETSI and 3GPP V2X approaches, it is also based on a CBR to CR limit table. Given a particular CBR, representing the overall measured congestion of the channel, if it is determined that the vehicles's CR exceeds the limit, the RRI will be increased such that the CR is brought below the limit. An SCI is then broadcast indicating the new RRI. When the CBR returns to a lower range and the CR can be increased, a new RRI will be chosen that maintains the new limit.

We also employ the DCC averaging mechanism for $\text{RRI}_{\text{Reactive}}$ and $\text{RRI}_{\text{CR\_limit}}$ where RRI transitions only occur after 1 second of CBR exceeding a threshold and RRIs are decreased after 5 seconds of lower measured CBR. This results in a more stable level of CBR for all vehicles. This is not applied for $\text{RRI}_{\text{Adaptive}}$ as the LIMERIC algorithm uses a moving average of CBR.

Fig. 2 illustrates the concept underpinning all three *RRI DCC* approaches (shown as per timeline *B*) with the default NR-V2X SB-SPS operation shown as per timeline *A*. In *A*, after transmission *T1*, congestion occurs. This results in a delay by a TRC congestion control mechanism or a packet drop. The consequence is that a packet is not transmitted in the next scheduled resource reservation slot i.e. a missed transmission (*MT*). As a result, an SCI is not transmitted so neighbouring vehicles believe the resource(s) to be free. However as the SB-SPS grant is maintained, and may be utilised in the future e.g. transmission *T3*, a collision on that resource can occur. In contrast, the proposed *RRI DCC* mechanisms shown in *B*, explicitly considers the RRI in the grant when adding a delay in the case of $RRI_{Reactive}$ and $\mathrm{RRI}_{\mathrm{Adaptive}}$ or packet dropping in the case of RRI_{CR_limit}. When transmission *T2* occurs, the new RRI is determined and an SCI is broadcast to all neighbouring vehicles. This ensures that neighbouring vehicles are informed of when the vehicle next intends to transmit and can utilise the free resources in the interim.

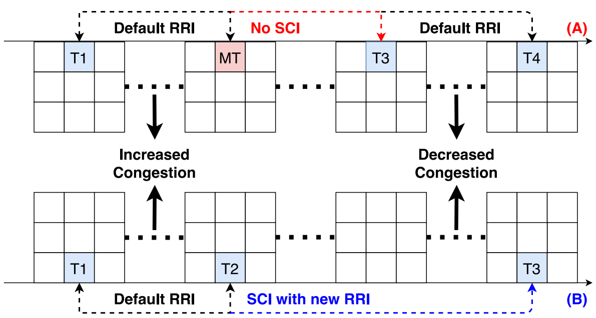


Fig. 2: RRI DCC approaches versus default NR-V2X SB-SPS approach.

IV. Limitations of Applying DCC Standards to C-V2X & NR-V2X

This paper sets out to firstly establish and quantify the efficacy of applying existing standardised approaches for congestion control to cellular vehicular communications. This is quantitatively evaluated using OpenCV2X [7], a V2X cellular sidelink model, with standardised congestion control models implemented to allow for this study. Both the NR-V2X (Rel. 16) and C-V2X (Rel. 14) versions of SB-SPS are considered. An important distinction between these is that RSSI filtering is removed for NR-V2X and only the RSRP of the most recent transmission is considered when determining reserved resources. Key simulation parameters are summarised in Table V, compatible with [8] to allow for comparison. All the models described in this paper have been developed to be open source and are available on the OpenCV2X website. Application packets are generated periodically (100ms) but only the most recent packet is transmitted i.e. older intermediate packets are dropped if a newer packet is generated.

A. *Performance of ETSI DCC*

The efficacy of applying the ETSI DCC mechanism (DCC Reactive), originally designed for the wireless ITS-G5 standard, directly to C-V2X (Rel. 14) is shown in Fig. 3a with NR-V2X (Rel. 16) performance shown in Fig. 3b. This is compared to SB-SPS performance without congestion control, labelled *C-V2X No DCC* and *NR-V2X No DCC* respectively.

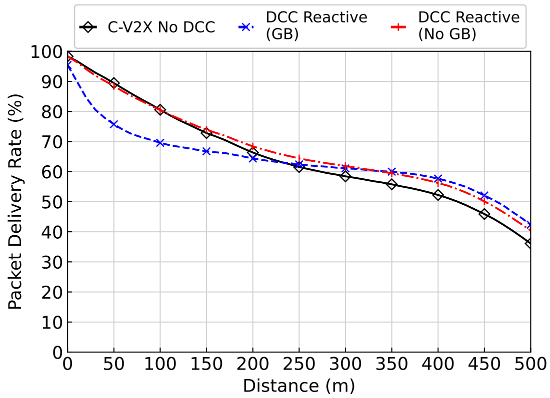
TABLE V: Simulation Parameters.

Parameter	**Value**
Vehicular scenario	
Vehicular density	0.46 veh/m
Road length	600 m
Number of lanes	3 in each direction (6 in total)
Vehicle Speed	50km/h
Vehicle Mobility	SUMO (step-length = 1ms)
Channel settings	
Carrier frequency	5.9 GHz
Channel bandwidth, No. subchannels	10 MHz, 3
Subchannel size	16 Resource Blocks
Application layer	
Packet size	190 Bytes
Transmission frequency (F_{Tx})	10 Hz
MAC & PHY layer	
Resource keep probability	0
RSRP threshold	-126 dBm
RSSI threshold	-90 dB
Propagation model	Winner+ B1
MCS	6 (QPSK 0.5)
Transmission power (P_{Tx})	23 dBm
Noise figure	9 dB
Shadowing variance	3 dB

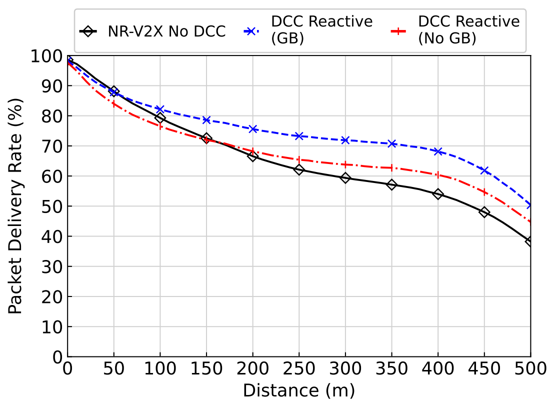
Two SB-SPS configurations are evaluated when considering the performance of DCC Reactive. The first assumes default behaviour where grant breaking is enabled (labelled *(GB)*), assuming the *sl-reselectAfter* parameter set to 1. This means that the grant is broken if a single reserved resource is not used i.e. other vehicles will perceive future grant resources to be free. The second configuration assumes grant breaking is disabled (labelled *(No GB)*).

It can be observed from Fig. 3a that *DCC Reactive (GB)* has a negative impact on the PDR of C-V2X, particularly at near distances up to 200m. This is for the same reasons that cause the decline of SB-SPS when scheduling aperiodic application traffic, as discussed in detail in [7]. As described in Section II-A, DCC introduces a delay in the packet inter-arrival time (mean of 252ms). If the packet inter-arrival time increases beyond a maximum of 198ms, assuming an RRI of 100ms ($2n$-2 where n=RRI) [7], this breaks the grant. Grant breaking leads to a rise in collisions due to vehicles contending for an increasingly small Candidate Set Resource (CSR) pool. To alleviate this, grant breaking can be disabled which marginally improves performance due to reduced resource rescheduling, as shown in Fig. 3a. However this marginal gain in PDR occurs despite a significantly lower CBR of ∼40% when compared with *No DCC* as shown in Fig 4b. This is because disabling grant breaking introduces an additional source of error, as discussed by Harri et al in [8]. If reserved resources go unused but the grant is maintained, an SCI is not sent. Thus, neighbouring vehicles may mistakenly believe the resources to be free. If the reserved grant is then utilised at a later point, this leads to unnecessary collisions.

Importantly, it can be seen from Fig. 3b that *DCC Reactive (GB)* can be effective in improving PDR when considering NR-V2X. This is due to the removal of the RSSI filtering

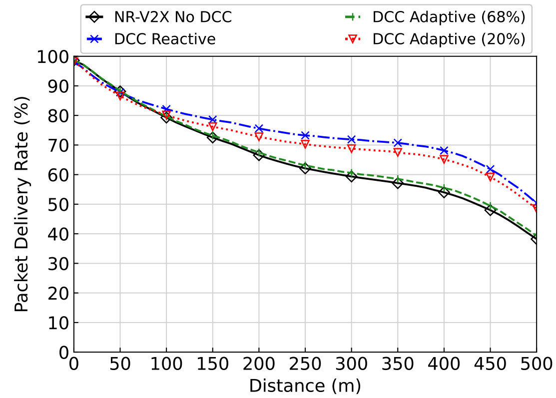


(a) ETSI DCC PDR (Reactive) Mode 4.

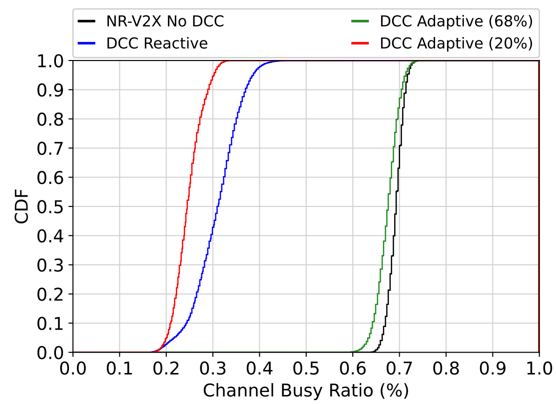


(b) ETSI DCC PDR (Reactive) Mode 2.

Fig. 3: Performance of ETSI DCC Reactive for C-V2X (Rel. 14) & NR-V2X (Rel. 16).



(a) ETSI DCC PDR (Reactive & Adaptive) Mode 2.



(b) ETSI DCC CBR (Reactive & Adaptive) Mode 2.

Fig. 4: Performance of ETSI DCC (Reactive & Adaptive) for NR-V2X (Rel. 16) with grant breaking enabled.

stage in NR-V2X SB-SPS which increases the number of possible CSRs available for selection, thereby eliminating the issue of limited CSR pool size and thus similar CSR selection. However this performance gain is limited to networks that demonstrate low congestion. At increased congestion, grant breaking will become prohibitive as the constant rescheduling increases the risk of vehicles selecting the same resource within an increasingly limited pool of free CSRs. As *DCC Reactive (GB)* performs best for a CBR of 20% we will consider this as the baseline for low congestion scenarios unless stated otherwise (labelled *DCC Reactive*) and will consider no grant breaking for higher congestion scenarios.

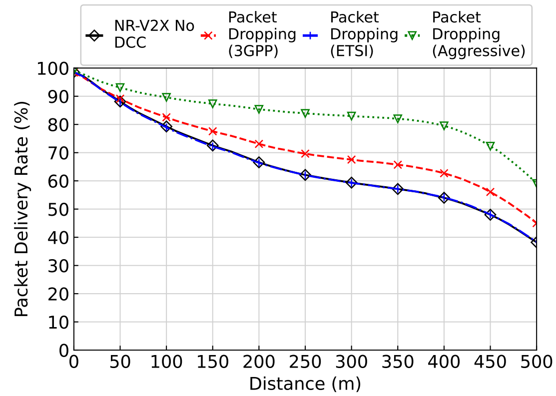
The performance of the other ETSI standardised approach, namely *DCC Adaptive* is now discussed. Based on LIMERIC [4], this adjusts packet rate transmission to converge to a target CBR. Default *DCC Adaptive* behaviour is assumed, where the CBR converges to a target of 68%. A CBR target of 20% is also evaluated to allow for direct comparison to *DCC Reactive*. The impact on PDR is shown in Fig. 4a. *DCC Adaptive* (68%) incurs identical performance to no congestion control with a slight reduction in the CBR experienced by vehicles, as shown in Fig. 4b. For a comparable CBR of 20%, *DCC Reactive* shows marginally better performance than *DCC Adaptive*. This is as a result of the higher packet inter-arrival times for the more stable *DCC Adaptive* which maintains an average of 300ms inter-arrival rate throughout. *DCC Reactive* has a more variable inter-arrival time, characterised by a mean of 252ms but ranging from 100ms to 400ms. Up to 50% of traffic arrives within 200ms. In accordance with textit2n-2 (where *n*=RRI) [7] as discussed earlier, this allows the SB-SPS grant to maintained more often, reducing the requirement for rescheduling and allowing for more accurate historical sensing. However the *DCC Adaptive* approach has advantages as it avoids the drawbacks of table based mechanisms such as CBR instability around fixed thresholds [5] and the necessity to fit the table to variable network demand.

B. *Performance of ETSI & 3GPP Packet Dropping*

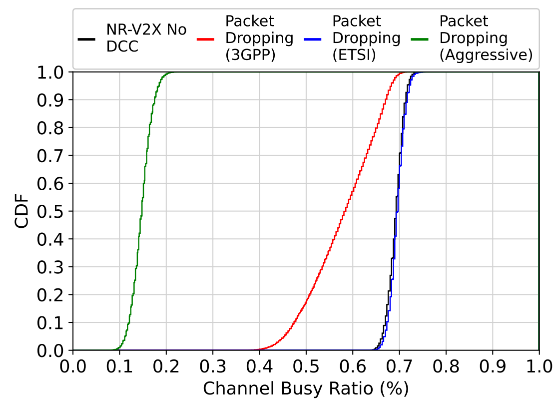
The previous section showed that the ETSI DCC mechanisms demonstrate some performance gain when directly applied to NR-V2X. However, this performance gain does not correlate with the reduction in CBR and will diminish at higher densities. This is caused by incompatibility between the packet generation rate and the SB-SPS scheduling algorithm. Hence, ETSI and 3GPP have proposed congestion control recommendations based on packet dropping. As described in II-B and II-C, this method of congestion control simply drops packets before transmission to maintain a specific CR limit according to a lookup table. Three CR limit lookup tables are considered in this paper, two of which are proposed as part of standardisation activities:

- The recently defined ETSI CR limit table as shown in Table III. A traffic priority of 6-8 is assumed as other priorities had negligible impact and this is the most restrictive table. This is labelled *Packet Dropping (ETSI)*.
- As part of a 3GPP working group, Qualcomm have also proposed a CR limit table [13]. This is labelled *Packet Dropping (3GPP)*.
- An adapted 3GPP CR limit table, with lower CBR thresholds that we have specified in order to more aggressively manage congestion i.e. to produce a mean CBR closer to 20% in line with the *DCC Reactive* scheme. This is labelled *Packet Dropping (Aggressive)*.

The PDR performance for packet dropping according to these CR limit tables can be seen in Fig. 5a. *Packet Dropping (ETSI)* performs identically to No DCC both in terms of PDR and CBR, as the ETSI CR limits associated with the CBR thresholds are high and hence not sufficiently responsive. *Packet Dropping (3GPP)* performs better due to a reduced CBR as shown in Fig. 5b, although this only translates into a PDR improvement of up to 9% at distances exceeding 150m as seen in Fig. 5a. Adopting a more aggressive approach to reducing CBR in the case of *Packet Dropping (Aggressive)*, improves PDR by up to 26% at distances beyond 100m. However, the improvement in PDR does not correlate with the significantly lower CBR.



(a) Packet Dropping PDR.



(b) Packet Dropping CBR.

Fig. 5: Performance of ETSI & 3GPP Packet Dropping for NR-V2X (Rel. 16).

V. RRI DCC FOR NR-V2X CONGESTION CONTROL

Importantly, irrespective of which standardised congestion control method is considered i.e. transmission rate control or packet dropping, both have the same marginal improvement on PDR. This is because of the disparity between the congestion control mechanism and the underlying SB-SPS scheduling mechanism based on the RRI, as described in Section III. To address this, we evaluate the three proposed adaptive RRI schemes described in Section III.

A. RRI DCC - Network Performance

The proposed *RRI DCC* congestion control schemes are compared against *NR-V2X No DCC*, *DCC Reactive*, *DCC Adaptive* (CBR target of 20%) and *Packet Dropping (Aggressive)*. In low density scenarios of 20% CBR, grant breaking will be enabled in contrast to higher density scenarios where grant breaking is disabled.

Fig. 6a shows the PDR performance of $RRI_{Reactive}$ outperforms *DCC Adaptive* by up to 9% PDR at near distances but Fig. 6b demonstrates less stability with respect to CBR. This is because it inherits the instability of the *DCC Reactive* table lookup mechanism. It exhibits considerably less mean colliding grants when compared to standardised DCC approaches as shown in Table VI. The mean colliding grants is a significant metric as it represents the resources utilised by 2 or more vehicles simultaneously, due to poor CSR selection in SB-SPS. Colliding grants can occur for four reasons:

1) A missed transmission, causing a vehicle to not send an SCI. Neighbouring vehicles will mistakenly believe a resource to be free in future reserved slots, when they may be utilised. This is denoted as γ_{MT} in Table VI.
2) In congested radio conditions, when no resources are determined to be free, vehicles will select resources with low RSRP measurements. This is denoted as γ_{NF} in Table VI.
3) The failure to decode the SCI of a neighbouring vehicle can result in a resource being seen as free. This can be as a result of propagation or interference on the resource and while the RSRP filtering will reduce the likelihood of selection it is still possible to be selected in congested scenarios similarly to γ_{NF}. This is denoted as γ_{NSCI} in Table VI.

TABLE VI: Absolute number of colliding grants & causation for each congestion control mechanism.

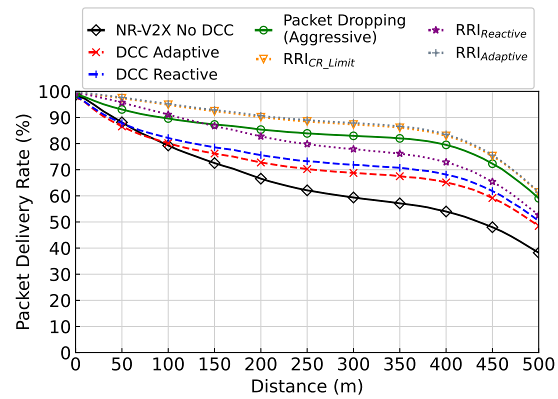
CBR	Congestion Control Mechanism	Mean Colliding Grants (γ)	γ_{MT}	γ_{NF}	γ_{TSim}	γ_{NSCI}
70%	*NR-V2X No DCC*	6552	-	4531	1276	744
20%	*DCC Adaptive*	10111	0	0	10111	0
	DCC Reactive	10615	67	72	10399	77
	Packet Dropping (Aggressive)	5964	44	0	5872	48
	$RRI_{Reactive}$	2116	-	1768	184	164
	$RRI_{CRlimit}$	1272	-	967	68	237
	$RRI_{Adaptive}$	1268	-	1084	74	111
60%	*DCC Adaptive*	7869	1366	3553	1175	1774
	$RRI_{CRlimit}$	4820	-	3864	557	398
	$RRI_{Adaptive}$	5398	-	3817	860	720

4) When neighbouring vehicles reserve the same resources within a single RRI as a result of similar selection windows. As neighbouring vehicles may have similar RSRP measurements they are likely to have similar CSRs pools which can result in selecting the same resource(s). This is denoted as γ_{TSim} in Table VI.

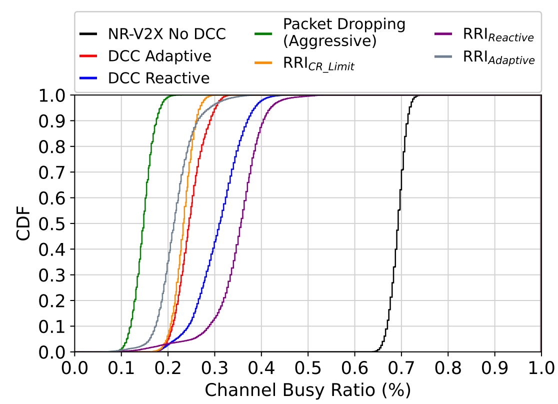
More notably, RRI_{CR_limit} and $RRI_{Adaptive}$ show significantly improved PDR e.g. an increase of up to 16% on *DCC Adaptive*, when compared to other standardised schemes, even those with comparable CBR. They also exhibit a low number of mean colliding grants, while maintaining high stability of CBR. The primary advantage of $RRI_{Adaptive}$ is that it avoids the drawbacks of table based mechanisms which we outlined previously.

DCC and packet dropping mechanisms are very susceptible to colliding grants due to γ_{MT} and γ_{TSim}, because of the incompatibility of their schemes with the SB-SPS RRI mechanism. When grant breaking is enabled for a low density scenario of 20% CBR, γ_{TSim} increases significantly as a result of constant rescheduling. In the case of no grant breaking for the higher density scenario, the γ_{MT} colliding grants increase due to missed transmissions resulting in incorrect CSR selection. Also, as the reserved resources are maintained for 5-15 subframes, as determined by the Resource Reselection Counter (RRC), recurring colliding grants represent multiple avoidable half duplex errors in the channel as well as increasing interference. This is evident in Table VI. In contrast, the *RRI DCC* approaches account for this and hence incur significantly less colliding grants by eliminating γ_{MT} and reducing γ_{TSim}. The variance in $RRI_{Reactive}$ CBR results in a higher number of colliding grants than the more stable RRI_{CR_limit} and $RRI_{Adaptive}$ approaches.

While RRI_{CR_limit} and $RRI_{Adaptive}$ demonstrate significantly higher PDRs (Fig. 6a), they both incur comparable application performance to *DCC Adaptive*, discussed further in Section V-B. This is attributable to aggressive congestion control, with CBR of approx. 20% (for comparison with schemes such as *DCC Reactive*). Given that this can result in under utilisation of the channel, a CBR of approximately 60% is considered in Fig. 7. This aligns with previous ITS-G5 studies that have investigated maximum throughput at 60% [6]. RRI_{CR_limit} and $RRI_{Adaptive}$ are compared against *NR-V2X No DCC* and *DCC Adaptive*. All perform comparably for this CBR target, exhibiting a PDR within 3% of each other, with $RRI_{Adaptive}$ performing best and RRI_{CR_limit} performing better than *DCC Adaptive*.



(a) Packet Delivery Rate.

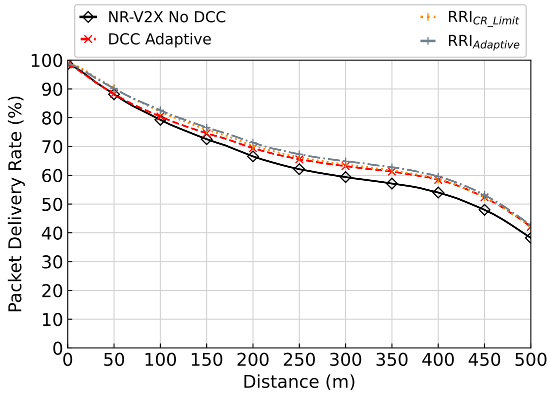


(b) Channel Busy Ratio.

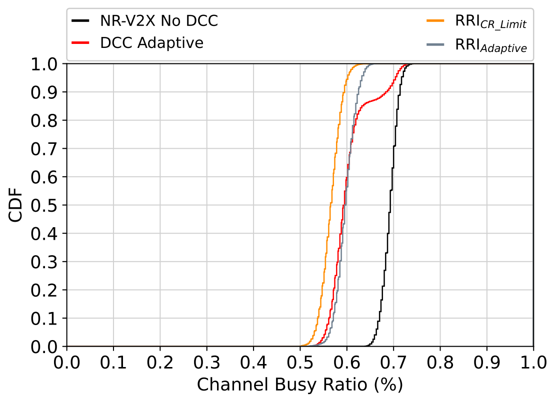
Fig. 6: RRI DCC versus standardised Congestion Control at 20% CBR (grant breaking).

B. RRI DCC - Application Layer Performance

Finally, it is important to consider the performance of the proposed congestion control mechanisms for the applications that they service, particularly as vehicular communications often has geotemporal relevance. Specifically, we consider the

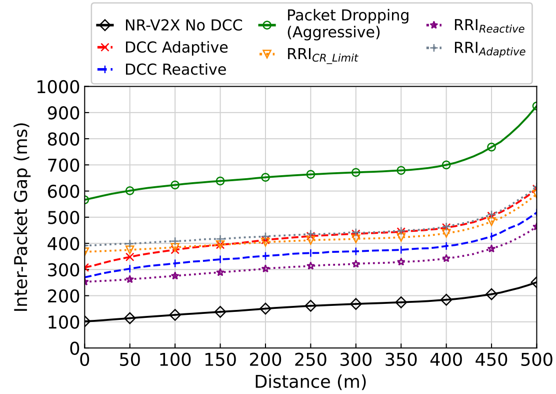


(a) Packet Delivery Rate.

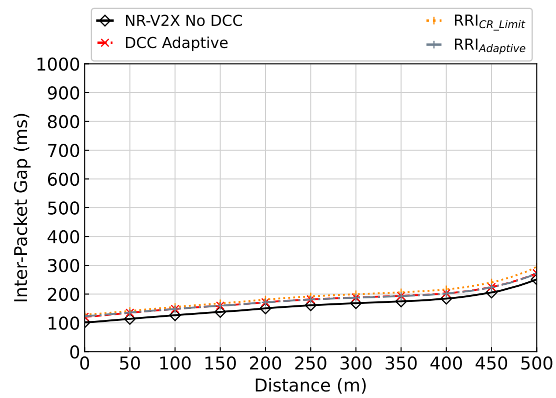


(b) Channel Busy Ratio.

Fig. 7: RRI DCC versus standardised Congestion Control at 60% CBR (no grant breaking).



(a) IPG at 20% CBR.



(b) IPG at 60% CBR.

Fig. 8: Inter-Packet Gap (IPG) performance of congestion control mechanisms.

impact on the Inter-Packet Gap (IPG), which represents the average elapsed time between receptions from neighbouring vehicles. We also consider mean awareness which is the percentage of neighbouring vehicles that a vehicle is aware of in a given communication range. The maximum lifetime of a CAM before it is discarded by a vehicle is 1 second.

In Fig. 8a, $RRI_{Reactive}$ demonstrates the lowest IPG while exhibiting better PDR (Fig. 6a), than standardised approaches except for the two other *RRI* schemes and *Packet Dropping (Aggressive)* which exhibits significantly higher IPG. Of the remaining mechanisms at the 20% CBR target, all exhibit an IPG of 360ms to 450ms on average with *RRI* approaches exhibiting slightly higher IPG than *DCC* variants. Neighbour vehicle awareness is shown in Table VII and is comparable with other approaches. The best performing schemes are RRI_{CR_limit} and *DCC Reactive* however RRI_{CR_limit} achieves better PDR performance and lower congestion than *DCC Reactive*.

TABLE VII: Neighbour Vehicle Awareness (200m-300m)

CBR Target	Congestion Control Mechanism	Awareness %	Std. Dev. %
70%	*NR-V2X No DCC*	91.5	1.5
20%	*DCC Adaptive*	91.6	1.6
	DCC Reactive	96.4	1.2
	Packet Dropping (Aggressive)	94.9	1.3
	$RRI_{Reactive}$	92.4	1.7
	RRI_{CR_limit}	96.4	1.2
	$RRI_{Adaptive}$	94.4	1.5
60%	*DCC Adaptive*	93.3	2.1
	RRI_{CR_limit}	97.4	1.0
	$RRI_{Adaptive}$	91.9	1.5

VI. Discussion

Several approaches have been defined by 3GPP and ETSI for congestion control for the C-V2X and NR-V2X standards. C-V2X is focused on the use of lookup tables for CBR to CR-limits which is the continued focus for NR-V2X [26]. Lookup tables have been widely studied in the context of ITS-G5 and have several limitations including CBR instability and fitting of the lookup table to the channel conditions. As such the investigation of congestion control mechanisms similar to *DCC Adaptive* is important as an algorithmic approach offers improved stability, fairness and can better manage diverse channel conditions. Accounting for SB-SPS scheduling, the current implementation of $RRI_{Adaptive}$ can provide this and allows for easy incorporation of other congestion control mechanisms beyond transmission rate control. While such an algorithmic approach does require parameter tuning, it may be possible to dynamically optimise such parameters through intelligent use of the sensing window to estimate the number of neighbouring vehicles. There is also scope to use the sensing window to determine the transmission rate of neighbouring vehicles to determine fair channel usage.

VII. Conclusion

Congestion control remains a key concern for vehicular networking where a reliable channel is paramount to performance of numerous safety critical services and spectrum is limited. This paper provides the first detailed quantitative evaluation of all existing congestion control standards for C-V2X and NR-V2X. Following this, a new approach called *RRI DCC* is proposed, comprising of three variants, in accordance with standards, and fully compatible with the SB-SPS mechanisms of both C-V2X and NR-V2X. We have shown that *RRI DCC* enables much higher performance in terms of PDR while maintaining comparable IPG and mean neighbour awareness when compared to existing standardised approaches. Open research questions also exist relating to Facilities layer congestion control that considers multiple simultaneous V2X services with diverse QoS requirements. Additionally, we will investigate the performance of *RRI DCC* mechanisms with respect to fairness and stability as well as dynamic parameter tuning.

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