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# RRI Adaptive: A Standards Compliant Approach for Equitable and Stable Congestion Control in C-V2X Networks.

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***Abstract*—A key topic of interest in all vehicular networking technologies is their ability to deal with dense radio environments as widespread deployment becomes a reality. This requires congestion control mechanisms to maintain adequate communication performance. The current Cellular Vehicle-to-Everything (C-V2X) and its successor New Radio V2X (NR-V2X) standardised congestion control approach is table-based, utilising packet dropping. As shown in past works by the authors of this paper, these approaches exhibit congestion instability and require extensive configuration. To overcome this, algorithmic approaches were standardised, namely ETSI's DCC Adaptive. Although this can be effective for wireless vehicular communications, it cannot be applied directly to NR-V2X/C-V2X due to incompatibility with the underlying radio scheduling approach, Sensing-Based Semi-Persistent Scheduling (SB-SPS). In previous work, the authors of this paper investigated in detail why this is the case and proposed an algorithmic approach that was compatible with the SB-SPS scheduler, namely $RRI_{Adaptive}$. This paper provides an in-depth evaluation of $RRI_{Adaptive}$. Importantly, its efficacy is evaluated not simply from the perspective of maintaining a desired channel load, but also from the perspective of maintaining effective application quality of service. This paper also describes the first study of fairness and stability in the context of C-V2X/NR-V2X congestion control. These are of increased importance, given dynamic channel conditions in vehicular scenarios, and reduced awareness due to degraded quality of service or vehicles starved of radio resources, may increase the likelihood of collisions.***

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

## I. INTRODUCTION

The NR-V2X standard [1] is an evolution of the C-V2X vehicular communication standard [2] proposed by the Third Generation Partnership Project (3GPP). Future connected and automated vehicles will need to accommodate multiple simultaneous V2X services, which may exhibit heterogeneous and sometimes stringent communication requirements. The foundation of these is the Cooperative Awareness (CA) service between vehicles (V2V) and infrastructure (V2I), Dynamic Environmental Notifications (DEN) e.g. emergency braking or emergency vehicle approaching, Cooperative Perception (CP) e.g. sensing objects in the environment. Given the limited spectrum dedicated to Intelligent Transportation System (ITS), it will be challenging for the network to manage dense vehicular radio environments while delivering effective performance.

As such, congestion control techniques, often referred to as Decentralised Congestion Control (DCC), are a significant area of research and have been thoroughly studied in the context of the more mature ETSI ITS-G5 [3] with several specified standards [4]. The 3GPP C-V2X/NR-V2X standards are less well developed and focus on table-based approaches, mapping the current level of congestion measured by the Channel Busy Ratio (CBR) to a Channel Occupancy Ratio (CR) limit, i.e. the proportion of the channel that a vehicle can access [5]. In [6], the authors of this paper investigated the performance of DCC approaches when applied directly to C-V2X/NR-V2X. We highlighted the instability of table-based approaches in terms of maintaining a steady CBR, as well as the need for significant parameter tuning based on the specific vehicular environment considered. Given the dynamic nature of a vehicular environment, this is not feasible.

As such, it is preferable to adopt an algorithmic approach, which may dynamically limit CR to maintain a congestion target, without instability or excessive tuning. In ITS-G5 this is provided by $DCC_{Adaptive}$ [4] based on the LIMERIC algorithm [7], but it cannot be applied directly to C-V2X/NR-V2X due to scheduling incompatibilities with SB-SPS. In our previous work [6], the focus was on developing congestion control mechanisms that work with the SB-SPS. A proposed solution was $RRI_{Adaptive}$ which adapts the resource reservation interval (RRI), which represents the period between transmissions, within the SB-SPS scheduler in line with the measured CBR and 3GPP channel occupancy.

This paper leverages those findings to provide a more comprehensive evaluation of $RRI_{Adaptive}$ with respect to the access layer (network) and also the performance of the application layer. We also describe what is to the best of the authors' knowledge, the first study in the literature to consider fairness and stability with respect to cellular vehicular congestion control. In summary, the contributions of this paper are as follows:

- A thorough evaluation of $RRI_{Adaptive}$ which is compliant with the NR-V2X/C-V2X SB-SPS scheduler and compared with ETSI DCC Adaptive approach. We specifically consider application layer performance as well as access (network) layer performance due to the spatio-temporal nature of vehicular services.

- The first study on fairness and stability when applied to cellular vehicular congestion control, considering the Jains fairness index [8], a measure of fair distribution of channel resources.

The rest of this paper is organised as follows: Section II gives an overview of the academic literature related to C-V2X congestion control. The proposed C-V2X $RRI_{Adaptive}$ DCC mechanism is presented in Section III and the simulation environment is described in Section IV. Finally, an evaluation is carried out in Section V with respect to access and application layer performance, as well as fairness and stability. Section VI provides concluding remarks.

## II. STATE OF THE ART IN CELLULAR VEHICULAR CONGESTION CONTROL

Initial academic literature mainly investigated congestion control mechanisms using table-based approaches. One of the first works to evaluate the impact of packet dropping for C-V2X is by Mansouri et al. [9]. Evaluates packet dropping performance based on the 3GPP C-V2X CR-limit tables. This paper highlights some of the issues we discuss in Section III where vehicles mistakenly choose the same channel resources. Hu et al. [10] provide an interesting real-world study in C-V2X congestion control at a test site in China with numerous LTE-V2X OBUs deployed to simulate a dense and congested environment. An adaptive MCS approach is adopted, whereby the MCS is increased when congestion occurs to fit the packets into 2 rather than 3 subchannels. This is effective in maintaining good PDR and CBR performance, but the study is limited in that it focuses on a single packet size. This is unlikely given that packet sizes frequently vary for vehicular services, referring to Renault and Volkswagen data sets [11] and the 3GPP guidelines for packet size distribution [12]. In such cases, the use of MCS adaptation for congestion control will only be impactful if subchannel occupation can be reduced, which is strongly dependent on the size distribution of the packet [13]. Wendland et al. [14] propose an approach based on an SB-SPS reservation splitting technique. The authors split a single SB-SPS grant into multiple sub-grants of lower frequency (e.g. 10Hz → 2 x 5Hz). When the network is congested, individual sub-grants can be disabled without interrupting the SB-SPS grant mechanism. This approach is the closest to the proposed $RRI_{Adaptive}$ 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. 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 $RRI_{Adaptive}$ approaches allow this to occur and works within the existing SB-SPS mechanism without requiring any changes.

Algorithmic congestion control techniques have also been explored. In the SAE standard, an approach combining mechanisms such as TRC, transmission power control (TPC) and MCS adaptation is proposed. The most prevalent of these is the SAE DCC mechanism [15] which uses power and rate control. The rate control algorithm is derived from the LIMERIC algorithm [7] and power control is based on The Stateful Utilization-based Power Adaptation (SUPRA) which is designed to control communication range [16]. The research in [17], [18], [19], [20] investigates the performance of the SAE standard. 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. Sabeeh et al. [21] also built a TPC-based solution. This was shown to be most effective with their own customised version of the SB-SPS scheduler, which added the Reselection Counter (RC) and colliding resource information to the SCI message. Choi et al. [22] use a deep-reinforcement learning approach to determine which mechanism to adopt, that is, TPC or TRC. This approach showed some marginal improvements over the simple table-based solution suggested by 3GPP, although it may be overengineered.

To the best of the authors' knowledge, there are no studies that focus on the fairness or stability of any of the C-V2X/NR-V2X congestion control techniques. Furthermore, they only consider the performance of the access layer of their investigated approaches. In contrast, this study addresses this challenge, which has also been extensively investigated in the context of ITS-G5/802.11p [23], [24], [25]

## III. RRI ADAPTIVE CONGESTION CONTROL FOR CELLULAR VEHICULAR SIDELINK

In [6], the authors of this paper comprehensively evaluated the performance of existing standardised TRC mechanisms for C-V2X networks. We highlighted the poor performance of the table-based approaches and showed that of the standardised mechanisms, the ETSI $DCC_{Adaptive}$ algorithmic approach (originally devised for ITS-G5 networks) performed the best.

However, we showed that all approaches, including $DCC_{Adaptive}$ exhibited much reduced performance due to their incompatibility with the underlying C-V2X/NR-V2X SB-SPS scheduler, which prohibits their direct applicability to such networks.

The reasons for this differ slightly depending on the way SB-SPS is configured, but both are problematic. SB-SPS can be configured in 2 ways to deal with missed transmissions; non-grant breaking (labelled No-GB) or grant breaking (labelled GB). A missed transmission is where there is no application packet to send, but a radio resource is reserved for use. In the No-GB case, a vehicle can miss several transmission opportunities (illustrated in the black dotted slots), but the resource remains reserved and can be used when the next application packet arrives. In the GB case, missed transmissions cause the grant to be broken and on reception of a new packet, a new grant will need to be selected for transmission. Both of these phenomena have significant impacts on the performance of the SB-SPS algorithm:

1) Both scenarios introduce a missed transmission; this is a free resource which could otherwise have been used by other vehicles i.e. SCI not sent.

2) No-GB, which keeps resources reserved for a vehicle, means that an SCI is not sent due to a missed transmission. Therefore, other vehicles will mistakenly view this resource as being free and may have selected the resource, resulting in a collision.
3) GB introduces issues around contention with frequent grant regeneration. This increases the number of collisions in the network.

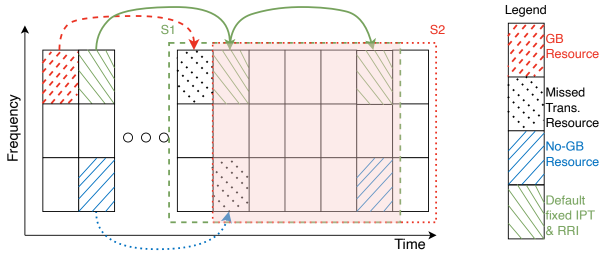


Fig. 1: *Impact of Missed transmission in grant breaking and non-grant breaking configurations.*

These impacts are illustrated in Fig. 1. S1, highlighted in green, represents the view of a selection window for a single vehicle, V1. V1's selection window contains resources which are reserved by other vehicles, but may go unused (black dotted). As a result, these resources will be discarded by V1. This represents phenomenon 1 in the above list. V1's selection window also contains a no-GB scenario, where the blue-striped resource is reserved by another vehicle who is maintaining, but not using, their grant, and as such V1 will determine this resource to be free. If the other vehicle resumes packet transmission on this resource, a collision will occur. This is phenomenon 2. Fig. 1 also illustrates phenomenon 3 (GB). A second vehicle, V2, creates a grant and sends its first packet (red dashed resource) but misses the next transmission. As a result, it relinquishes its grant. When it next receives an application packet, it must select a new resource. The consequence of this is that its selection window S2 (red dashed line) may overlap heavily with the S1 (shaded area), increasing contention, and increasing the chance of similar CSR selection.

Importantly, these three phenomena contribute to the poor performance of SB-SPS with the current generation of congestion control mechanisms based on TRC approaches. This is because TRC approaches (packet drops or packet delays) lead to missed transmissions.

As such, it is vital that any congestion control mechanism accounts for the impact that missed transmissions have on the SB-SPS scheduler. To do this, we proposed $RRI_{Adaptive}$ which adapts the LIMERIC linear adaptive message rate control algorithm (forming the basis of $DCC_{Adaptive}$), for the C-V2X/NR-V2X standard. It adapts this algorithm in 3 ways:

1) For each transmission $\delta$ is compared to CR. If $\delta$ exceeds CR, an adaptation of the SB-SPS RRI parameter takes place. This is a significant parameter as it updates when SB-SPS expects to send a packet, so if it is accurate, missed transmissions will not occur.
2) In such cases, the CR is recalculated with ever-increasing RRIs up to 1000ms. Once CR does not exceed $\delta$, that is, the channel occupancy is sufficiently reduced, then this is the RRI used for subsequent transmission.
3) Transmission occurs, and the intermediary packets are dropped to avoid transmission in the intermediate time slots.

This enables $RRI_{Adaptive}$ to operate in compliance with 3GPP standards for congestion measurement and channel management, i.e. CBR and CR measurements, while also complying with the default SB-SPS MAC scheduling operation. It should be noted that there is no means to update the RRI after its transmission in the SCI and, as such, no means of using equation B.2 from [26]. This equation updates the delay depending on current channel conditions and allows for early termination of a specific delay. Although this is possible in ITS-G5, it is not possible in C-V2X/NR-V2X due to the grant mechanism. As such, once the RRI is sent, the delay is fixed until the next transmission.

Fig. 2 illustrates the concept underpinning the $RRI_{Adaptive}$ approach. The default SB-SPS performance is highlighted in green, showing the SB-SPS RRI parameter (expected packet transmission time) consistent with the inter-packet time (IPT). This is how SB-SPS expects to operate with packets arriving in a predictable periodic manner.

When congestion occurs, a TRC mechanism such as $DCC_{Adaptive}$, which is not integrated with SB-SPS, leads to IPT being inconsistent with the RRI. This can be seen in Fig. 2 where the first transmitted packet (red dash) creates a grant that subsequently reserves a future resource (black dotted). TRC is then applied, such as $DCC_{Adaptive}$ as congestion occurs. This results in the black dotted resource going unused and a missed transmission occurring. Subsequently, the resource may then be used in future (assuming No-GB), which results in both phenomena which we discussed earlier. Finally, in Fig. 2, we also observe the impact of $RRI_{Adaptive}$, where the TRC $\delta$ parameter is compared to CR to determine the updated RRI (purple). This allows the intermediate reserved resource to be 'skipped', reducing CBR in the channel without introducing a missed transmission in SB-SPS thereby interfering with the SB-SPS sensing procedure.

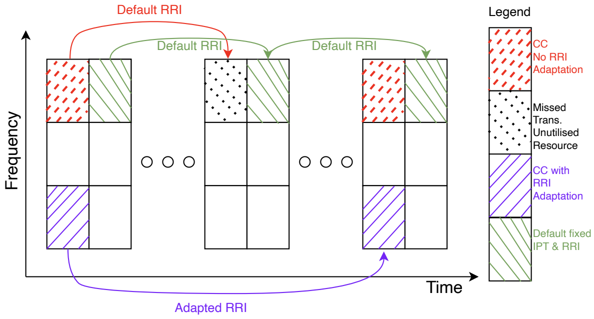


Fig. 2: $RRI_{Adaptive}$ approaches versus previous approaches.

## IV. SIMULATION ENVIRONMENT

The evaluation carried out in this paper uses the network simulator OMNeT++ and OpenCV2X, a C-V2X/NR-V2X mode 4 and mode 2 sidelink model [27]. Key simulation parameters are summarised in Table I.

TABLE I: 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** | |
| SB-SPS | No Grant Breaking (No-GB) |
| 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 |

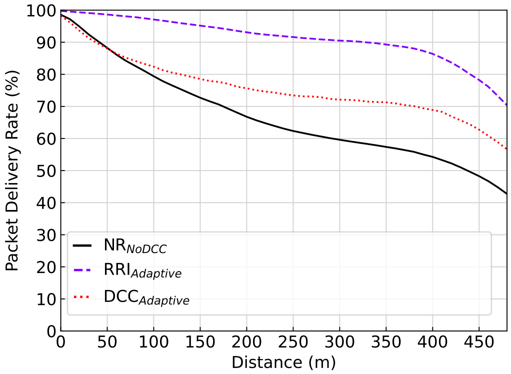
The performance of $RRI_{Adaptive}$ is evaluated against that of DCC Adaptive, which was shown to be the best performing of the currently standardised congestion control approaches in [6]. In this study, three network configurations are considered, all based on the same road network as described in Table I. The first two are identical except that in both cases the target network load is configured to 20% and 60% CBR, respectively. The final considered scenario is a long-form simulation that represents a dynamic scenario where the channel load changes over time. This is designed to evaluate the stability of congestion control mechanisms with varying densities of network traffic. This is achieved in a stepwise manner with only 25% of the vehicles transmitting initially and subsequently increasing by 25% over 20s time slots. The channel load is then lowered in a similar manner with 25% less vehicles transmitting per 20 second interval.

As we explicitly consider the fairness of $RRI_{Adaptive}$ when compared to $DCC_{Adaptive}$, we use the Jain's fairness index [8]. This well-known index operates based on the desired transmission rate for each vehicle compared to their allocated rate. The goal is to achieve a score of 1 which is considered perfect fairness with low scores indicating unfairness where vehicles are starved of radio resources. We also investigated the convergence of congestion control techniques in terms of CBR and the stability of CR and message transmission rate for each node throughout our simulation study.

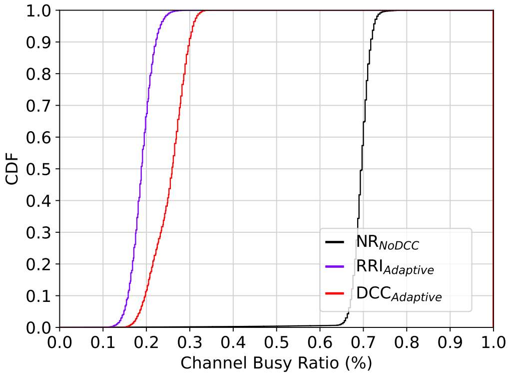
## V. SIMULATION RESULTS

This section evaluates NR-V2X in terms of no congestion control $NR_{NoDCC}$, the standardised DCC Adaptive approach $DCC_{Adaptive}$ and the proposed $RRI_{Adaptive}$ approach. Specifically, performance across 3 areas are considered; traditional access (network) layer performance, application layer performance, and finally a thorough analysis with respect to fairness and stability.

### A. Adaptive RRI - Access layer Performance



(a) Packet Delivery Rate.

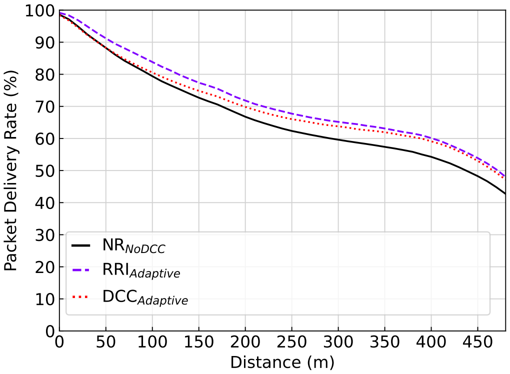


(b) Channel Busy Ratio.

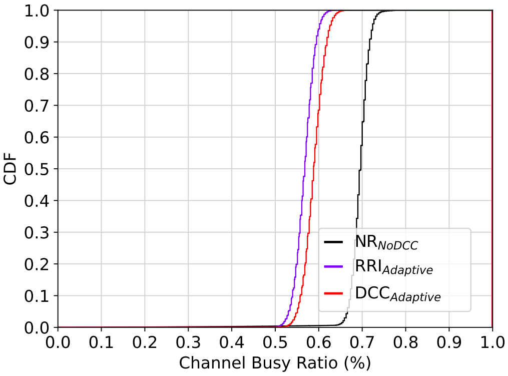
Fig. 3: Comparative congestion control at 20% CBR.

The first network configuration considers a target load of 20% CBR in the network. While this is excessively restrictive, it is used to highlight the impact of significant packet dropping on the performance of the SB-SPS scheduler. A similar phenomenon might occur in a network simultaneously hosting multiple services such as CAMs, CPMs, DENMs and Local Dynamic Map packets. In such cases, while the load in the network will be significantly higher than what we consider as a benchmark (a single service without congestion control), it will have the same effect; it allows for comparison on the performance of the congestion control techniques in a scenario where there is a significant level of packet dropping. This is to demonstrate how SB-SPS performance can be degraded when there is no effective means of maintaining the SB-SPS RRI.

Fig. 3 clearly shows the significant improvement in PDR performance between $RRI_{Adaptive}$ and $DCC_{Adaptive}$ with the corresponding CBR performance shown in Fig. 3b. This is especially notable at the shorter distances between transmitting and receiving pairs. The PDR performance of $DCC_{Adaptive}$ in the range of 0-100 m is comparable to $NR\text{-}V2X_{NoDCC}$, irrespective of a reduction of  50% in CBR reduction. It can be seen that only at ranges beyond 100m are there significant performance increases for $DCC_{Adaptive}$. Furthermore, it should be noted that $DCC_{Adaptive}$ does not manage to maintain the target 20% CBR as can be seen in Fig. 3b, while $RRI_{Adaptive}$ is more effective at meeting the desired CBR target.



(a) Packet Delivery Rate.



(b) Channel Busy Ratio.

Fig. 4: Comparative congestion control at 60% CBR.

The second network configuration considered has a CBR target of 60%, considered the default in many academic papers [28], for both congestion control mechanisms. This represents a more likely network target load. In this case, there is a minimal performance improvement of $RRI_{Adaptive}$ over $DCC_{Adaptive}$ as shown in Fig. 4a and both mechanisms are effective in meeting the CBR target of 60% as shown in Fig. 4b. This is due to the much smaller reduction in CBR compared to $\mathbf{NR_{NoDCC}}$. The less congested scenario means that packet dropping/delay is not as prevalent as the previous scenario.

### B. Adaptive RRI - Application Layer Performance

Next, we investigate the performance of congestion control mechanisms relative to application layer KPIs. The primary KPIs considered in this study are the inter-packet gap (IPG) and the mean awareness of the neighbour in the 200-300 m range. IPG represents the average inter-packet arrival rate on a single vehicle and is compared over distance between the sender and receiver. This metric indicates the regularity of updates that a vehicle receives from its neighbouring vehicles at a given range. It is impacted by channel conditions and congestion control mechanisms. Mean neighbour awareness represents the proportion of vehicles in the 200m-300m range of which a vehicle is aware, i.e. it has received a CAM from those vehicles and knows their position, heading, speed, etc.

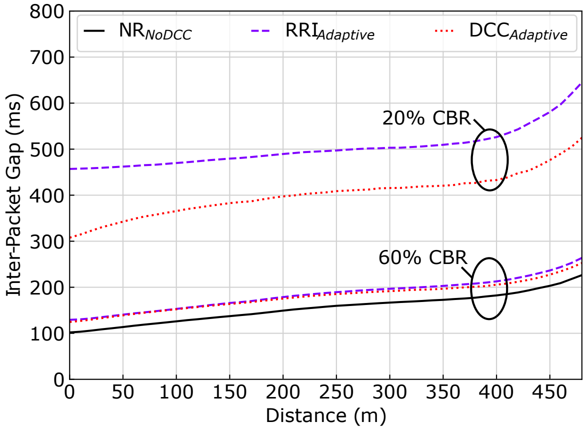


Fig. 5: Comparative Inter-Packet Gap.

Figure 5 represents the performance of all congestion control mechanisms across both CBR targets. It can be seen that at the 20% target CBR, the IPG of the $RRI_{Adaptive}$ is higher with a performance difference of 100 ms. This can be mainly attributed to $DCC_{Adaptive}$ exhibiting a higher CBR of 10%, i.e. not meeting the defined 20% target as shown in Fig. 3b, and thus transmitting packets more frequently. The 60% CBR target scenario provides a more fair comparison between the two methods and here they exhibit near identical IPG but with $RRI_{Adaptive}$ exhibiting a marginally lower CBR. It is clear in all cases that applying any of these congestion control mechanisms will result in an increase in IPG, as illustrated by the increase over the $NR_{No\ DCC}$ but this represents the trade-off between maintaining a high PDR at the expense of latency.

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

| CBR Target | Congestion Control Mechanism | Awareness % | Std. Dev. % |
|---|---|---|---|
| 70% | *NR-V2X-No DCC* | 91.7 | 0.6 |
| 20% | *DCC Adaptive* | 91.5 | 1.7 |
| | $RRI_{Limeric}$ | 94.8 | 0.6 |
| 60% | *DCC Adaptive* | 97.2 | 0.5 |
| | $RRI_{Adaptive}$ | 97.8 | 0.4 |

The mean results of neighbour awareness are more notable as shown in Table II. In most cases, it is clear that applying congestion control can improve awareness. In the congest 20% scenario it is clear that $RRI_{Adaptive}$ offers improved awareness over $DCC_{Adaptive}$ with comparable performance in 60%.

### C. Fairness and Stability

This section investigates the performance of all congestion control approaches in both network configurations in terms of fairness and stability. It also introduces a long form simulation as described in Sec. IV, where the congestion in the network rises to a high peak and then falls back to a low state of congestion. This is designed to show how $RRI_{Adaptive}$ better handles dynamic changes in congestion and how such changes impact stability and fairness. Fairness between vehicles will be evaluated using the Jains fairness index as described in Sec. IV. Finally, we investigate the average transmission rate over time with confidence intervals for both congestion control mechanisms, as well as the Channel Occupancy Ratio (CR) over time. These further highlight the fairness and stability of the evaluated mechanisms.

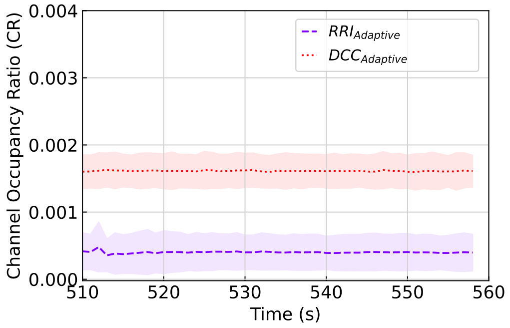
TABLE III: Jain's Fairness evaluation

| **CBR Target** | **Congestion Control Mechanism** | **Fairness %** |
|---|---|---|
| 20% | *DCC Adaptive* | 100 |
| | $RRI_{Adaptive}$ | 99.75 |
| 60% | *DCC Adaptive* | 99.41 |
| | $RRI_{Adaptive}$ | 99.98 |
| 60% | *DCC Adaptive (longform)* | 95.66 |
| | $RRI_{Adaptive}$ *(longform)* | 99.07 |

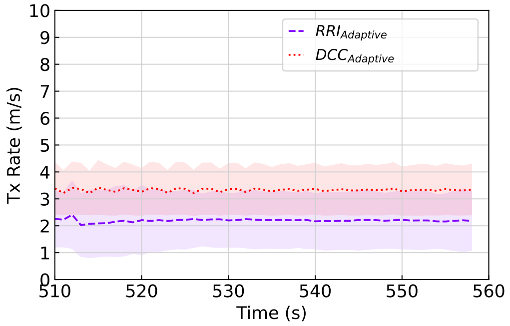
In Table III, when considering the two network configurations already evaluated in this paper, that is, 20% and 60%, it can be observed that both congestion control mechanisms demonstrate comparable fairness. However $RRI_{Adaptive}$ demonstrates improved fairness of 3.5% when considering the long-form simulation that shows fluctuations in congestion levels.

All the applied congestion control mechanisms are based on the LIMERIC algorithm, and this is well known to operate in an effective and fair manner. The only explanation for the difference in performance is integration with the underlying scheduling approach. The greater challenge is in managing stability effectively, which is where $DCC_{Adaptive}$ exhibits drawbacks due to its incompatibility with the scheduling approach.

In Figures 6a and 6b, we consider the CR and the average transmission rates to examine stability performance. In all cases, the CR cannot exceed 0.003 and the transmission rate cannot exceed 10Hz. In particular, $DCC_{Adaptive}$ exhibits a higher CR and therefore transmission rate, especially for a target of 20% CBR, which explains the higher measured CBR shown earlier in Fig. 3b. For both mechanisms, there are no significant changes in the confidence intervals of both metrics, which are shown in shaded areas. This aligns with the fairness data shown earlier in Table III, with both showing high stability and fairness.

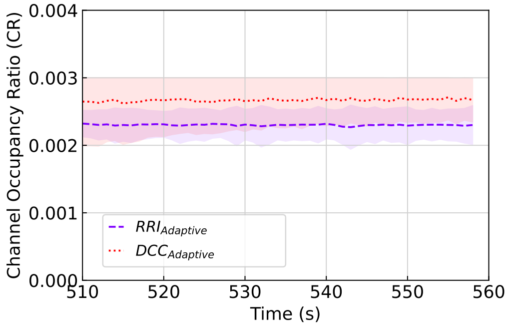


(a) Channel Occupancy Ratio.

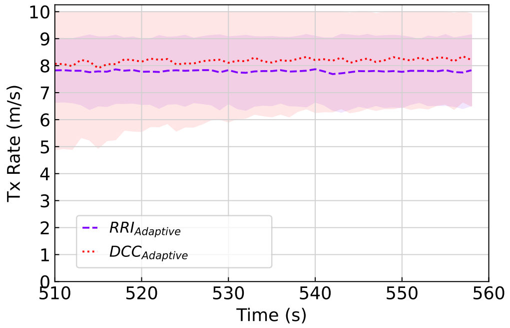


(b) Average Message Rate.

Fig. 6: Comparative stability statistics at 20% CBR.

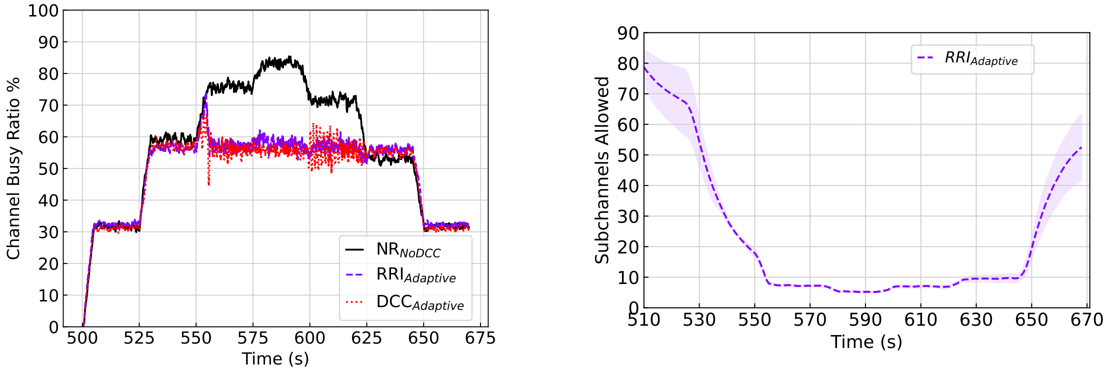


(a) Channel Occupancy Ratio.

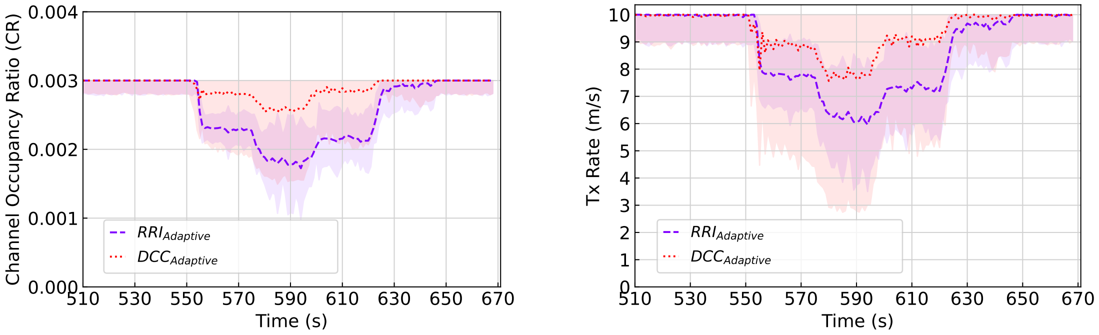


(b) Average Message Rate.

Fig. 7: Comparative stability statistics at 60% CBR.



(a) CBR (b) Subchannels allowed per vehicle



(c) CR (d) Transmission Rate (Tx)

Fig. 8: Long-form variable CBR simulation. Comparative stability statistics for a long-form simulation exhibiting fluctuating congestion in the channel.

For the 60% target CBR, $RRI_{Adaptive}$ exhibits a more stable performance. While both congestion control mechanisms exhibit comparable fairness, they diverge in terms of CR and message rate stability. In Figure 7, it is clear that $DCC_{Adaptive}$ exhibits higher CR and message rate. It is clear from the 95% confidence intervals (shaded areas) that $DCC_{Adaptive}$ exhibits reduced stability, particularly when examining transmission rates that can fluctuate by up to 5Hz early in the simulation and always exceed the rates maintained by $RRI_{Adaptive}$.

Long-form simulation results are shown in Fig. 8a. $NR_{NoDCC}$ (black line) represents the baseline network performance without applying congestion control techniques. When $RRI_{Adaptive}$ and $DCC_{Adaptive}$ are applied, both reduce congestion i.e. CBR by over 20% in most densely congested time period between 550s-625s. However, it is clear that $RRI_{Adaptive}$ is more effective at maintaining a stable CBR while converging to the target CBR, especially when congestion is reduced between 600 and 625 s.

It is clear that $RRI_{Adaptive}$ is more stable, and this is verified by examining the CR and transmitter rate performance of both approaches, as shown in Fig. 8c and Fig. 8d. Fig. 8c clearly shows how CR is stepped down by each approach and how $DCC_{Adaptive}$ exhibits much more variables CR confidence intervals. This translates into a more extreme divergence in transmission rate as shown in Fig. 8d, especially at the most dense time period 590s where the transmission rate can vary from 3Hz to 10Hz. While, $RRI_{Adaptive}$ does show some instability ranging from 4Hz to 8Hz, it still exhibits a significant improvement.

The reason why $RRI_{Adaptive}$ exhibits better stability can be visualised in 8b, which shows how the underlying parameter $\delta$ is translated into the effective number of subchannels allowable for each vehicle per second. It is clear that initially vehicles can use a significant number of resources, that is, up to 80 subchannels the entire channel. The application running on each vehicle only requires 10 subchannels, demanding 1 subchannel per transmission and 10 transmissions per second. As such, congestion control mechanisms are only applied when $\delta$ drops below 0.003 i.e. the maximum CR needed for each vehicle or fewer than 10 subchannels per second. At this stage, stability is high because the LIMERIC algorithm is strict on the number of resources available for each vehicle. This is demonstrated by the confidence interval 95% (shaded area) tightly bound to the average in this area (dashed line). As such, it is operating effectively and results in better stability performance in terms of CR and average transmission rate, as previously shown. The challenge for $DCC_{Adaptive}$ is due to its incompatibility with the SB-SPS scheduling mechanism.

This results in inconsistent performance for the channel as a result of increased collisions which can result in increased CBR. Additionally, the introduction of missed transmissions and the consequent additional collisions can impact channel congestion. This can result in oscillations in CBR, where a collision occurs, reducing measured congestion, thereby resulting in rates increasing and thus CBR increasing again, causing a back off in transmission rate. These oscillations can be clearly seen in Fig. 8d and are much more severe than any exhibited by $RRI_{Adaptive}$.

The ultimate conclusion with respect to both fairness and stability is that $RRI_{Adaptive}$ can maintain a stable target CBR while achieving high levels of fairness amongst vehicles. Importantly, it can do with high fluctuations in congestion in the network.

## VI. CONCLUSION

This paper has introduced and thoroughly analysed a DCC approach for C-V2X and NR-V2X in $RRI_{Adaptive}$ and draws three conclusions from this. First, our proposed approach can significantly improve the scheduling performance of existing techniques, improving PDR performance while maintaining low IPG and high neighbour awareness, thus not degrading application performance. The second conclusion is that the introduction of $RRI_{Adaptive}$ allows a DCC mechanism to overcome the limitations of table-based approaches, specifically the CBR instability and the requirement for table tuning. The final aspect is that we have shown that the proposed solution operates in a more fair and stable manner than the current approaches, and this is a key for vehicular networks to ensure the highest levels of safety. This is the first comprehensive study of a C-V2X/NR-V2X DCC mechanism with a focus on both fairness and stability.

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