Exploring NR-V2X Dynamic Grant Limitations for Aperiodic Traffic

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Abstract: The recent 3GPP NR-V2X standard (Rel. 16) has largely built upon its precursor Cellular-V2X (Rels. 14 & 15) but has introduced new approaches for dealing with application traffic exhibiting aperiodic arrival rates in the sidelink. This is vital as safety services based on ETSI Cooperative Awareness Messages (CAMs) and Decentralised Environmental Notification Messages (DENM) exhibit such characteristics. It is further envisaged that future vehicular services will also exhibit high aperiodicity to support increased autonomy. In this paper we quantitatively evaluate the reasons why the Sensing based Semi-Peristent Scheduling (SB-SPS) mechanism performs poorly when scheduling aperiodic traffic. We then provide the first in-depth evaluation of the NR-V2X Dynamic Grant mechanism in contrast to schemes that parameterise the existing C-V2X SPS algorithm and evaluate the performance of alternative dedicated scheduling mechanisms specifically designed for aperiodicity. This paper highlights that the level of aperiodicity exhibited by the application model greatly impacts scheduling performance, both for the default SB-SPS and dedicated approaches. As such we conclude that a novel aperiodic scheduling mechanism must be devised, or more promisingly, an approach to enable application traffic to mimic periodic characteristics allowing it to co-exist with the existing scheduling approach.

1 INTRODUCTION

The Third Generation Partnership Project (3GPP) has specified mobile standards to support V2X (vehicle to everything) communications as an alternative to the existing wireless standards based on IEEE 802.11p. These standards, known as Release 14 (3GPP, 2016) and Release 15 (3GPP, 2019) support vehicle to infrastructure/network (V2I/V2N) communications via the traditional *Uu* interface but also allow for direct communication between vehicles (V2V) via the *PC5* sidelink interface. The radio resources necessary to facilitate V2V communications can be selected and managed by the cellular network (Mode 3) or selected autonomously by the vehicles (Mode 4) using the distributed scheduling algorithm, Sensing Based Semi-Persistent Scheduling (SB-SPS). The specification in Rel. 14 and Rel. 15, known as Cellular-V2X (C-V2X) has acted as the basis for the New Radio (NR) specification in 3GPP Release 16 (3GPP, 2020) with Mode 4 forming the basis for NR-V2X Mode 2.

The original focus of the 3GPP Rel. 14 standard was on traffic safety and efficiency applications with the assumption that safety messages (CAMs) would be shared periodically between vehicles. This assumption does not typically hold true as ETSI message generation rules (ETSI, 2019a) specify CAM transmission based on vehicle dynamics. Furthermore, the 3GPP has also specified enhanced V2X (e-V2X) applications for connected and automated vehicles including platooning, extended sensors, advanced and remote driving that will need to support aperiodic application traffic patterns.

However, the transmission of aperiodic application traffic has a large impact on the operation of the SB-SPS MAC scheduling mechanism. It was designed to assume periodic arrival rates thereby enabling accurate prediction of free radio resources. Aperiodic traffic which by it's nature does not have a strict pattern introduces significant inconsistencies to the historical sensing inhibiting this prediction. This may result in C-V2X and its evolution NR-V2X being unable to adequately meet application requirements, thus rendering them unreliable. NR-V2X has introduced a dynamic grant mechanism to deal with this and additionally includes some changes to the SB-SPS historical sensing mechanism. A detailed quantitative study is however missing from literature to evaluate if this can adequately address high levels of aperiodicity. As such an open research challenge

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is to fully understand the cause of SB-SPS and dynamic grant performance degradation when dealing with aperiodic application traffic and to redesign the C-V2X MAC scheduling algorithm to more reliably support such aperiodicity, ideally in co-existence with the current scheduling algorithm.

This paper provides an in-depth study to determine the precise reasons and conditions under which the C-V2X and NR-V2X SB-SPS algorithms exhibit significant performance degradation when supporting aperiodic application traffic across a variety of vehicular densities. Next, the paper investigates the performance limitations of NR-V2X dynamic grant, highlighting its shortcomings as well as the conditions under which it can function adequately. To address the shortcomings, either a dedicated scheduling approach should be devised or a means of enabling aperiodic traffic to mimic periodic characteristics to fit with the existing scheduling approach. Finally this paper evaluates the viability of some alternative dedicated scheduling approaches.

The main contributions of this paper are:

- An indepth quantitative study of the behaviour of the C-V2X and NR-V2X SB-SPS algorithms when faced with aperiodic application traffic characteristics.
- An evaluation of the effectiveness of the NR-V2X dynamic grant mechanism in order to gain deeper insight into how aperiodic application traffic, characteristic of future e-V2X 5G NR applications, can be better supported.
- A study of how dedicated aperiodic scheduling mechanisms could perform and co-exist with default SB-SPS for hybrid application models.

The remainder of the paper is organised as follows. Section 2 describes the related literature with Section 3 describing the operation of the PHY & MAC layers of C-V2X and NR-V2X. Subsection 4.1 provides a detailed simulation study of the challenges faced by SB-SPS in supporting aperiodic application traffic for an ETSI CAM application model. Subsection 4.2 highlights the shortcomings of the NR-V2X dynamic grant mechanism in supporting fully aperiodic services, with Subsection 4.3 highlighting the impact of considering hybrid periodic vs aperiodic application arrival rates. Finally Subsection 4.4 shows that dedicated aperiodic scheduling schemes can partially address the highlighted shortcomings but not for high levels of aperiodicity which will be likely in practice. Section 5 concludes the paper with a summary of key findings and a discussion on the most beneficial future solution.

2 RELATED LITERATURE

Existing literature has not quantitatively evaluated whether Rel. 16 NR-V2X, including dynamic grant, can adequately support aperiodic traffic, with evaluations largely focusing on the Rel. 14 C-V2X SB-SPS standard. Such a study is vital as ETSI CAM and DENM transmissions are fully aperiodic and these will form the basis for future e-V2X services to support increased autonomy.

Existing studies have stated that SB-SPS has been designed to better facilitate periodic traffic (Bazzi, 2019; Gonzalez-Martín et al., 2019). Molina-Masegosa et. al (Molina-Masegosa et al., 2020) conducted a study contrasting C-V2X Mode 4 with 802.11p for periodic and aperiodic application models, as well as variable packet sizes. They further study adapting the resource reservation interval by balancing re-selections against occurrences of wasted resources using three strategies. Notably, the authors suggest that the SB-SPS mechanism is fundamentally counter-productive for aperiodic traffic and highlight that further dedicated schemes are required. They do not consider grant breaking or dynamic grant in their evaluation.

Similarly, Bartoletti et. al (Bartoletti et al., 2021) also investigated the performance of C-V2X Mode 4 with grant breaking for aperiodic traffic patterns, highlighting its poor performance. The authors conclude that while wasteful of resources, disabling grant breaking performs adequately when dealing with aperiodic traffic. The same authors go on to investigate SB-SPS for the NR-V2X Mode 2 standard in (Todisco et al., 2021). The findings were interesting in that they showed that the removal of RSSI filtering and RSRP averaging in Mode 2 detrimentally impacts SB-SPS performance for aperiodic traffic. Only the reintroduction of these features results in similar performance to C-V2X Mode 4. As such they conclude using a static RRI within SB-SPS scheduling is not effective. Both studies do not investigate the NR-V2X dynamic grant mechanism nor are dedicated aperiodic scheduling schemes considered.

Romeo et. al (Romeo et al., 2020a) consider aperiodic traffic in the form of Decentralized Environmental Notification Messages (DENMs), sent to alert vehicles of hazardous road conditions. The authors examine the impact of tuning SB-SPS parameters to support aperiodic packets e.g. by reducing sensing windows, selection windows and selection probability (*RSel*) when providing CSRs to the MAC layer. Periodic CAM transmissions with single DENM packets are considered as opposed to a traffic pattern/model with aperiodic arrival rates. In a later study (Romeo et al., 2020b), DENM re-transmissions are considered including the likelihood of two or more vehicles arbitrarily choosing the same resource, with the subsequent collision being maintained for the duration of the grant, thereby impacting successful receipt of the DENM. However, the authors consider a one time reservation to mimic the Dynamic Grant mechanism but this operates using the C-V2X Mode 4 SB-SPS standard i.e. includes RSSI filtering and RSRP averaging. As such it is does accurately model NR-V2X Mode 2.

Finally, Lusvarghi et. al (Lusvarghi and Merani, 2020) investigate a hybrid application model using aperiodic and periodic traffic. The authors do not consider NR-V2X Mode 2 but rather examine C-V2X Mode 4 performance. Their findings show that periodic traffic is prioritised, resulting in poor performance for aperiodic traffic. This disparity is worsened when large aperiodic packet sizes are considered e.g. 1000 Bytes, due to high subchannel occupation.

3 OPERATION OF THE C-V2X & NR-V2X SIDELINK

The following sections describe the most important aspects of the PHY and MAC layers of C-V2X Mode 4 and NR-V2X Mode 2.

3.1 C-V2X Physical Layer

The PHY layer of 3GPP Rel. 14 C-V2X implements Single-Carrier Frequency Division Multiple Access (SC-FDMA). In the time domain, resources are organised into subframes of 1 ms, which are further grouped into frames of 10 ms. In the frequency domain, the channel is divided into subcarriers of 15 kHz. These subcarriers are grouped into Resource Blocks (RBs), with each RB containing 12 subcarriers and spanning over 1 subframe. Unlike the conventional resource structure of LTE, C-V2X groups RBs into subchannels. The number of RBs per subchannel and the number of subchannels are configurable but limited by the allocated bandwidth, which can be of 10 or 20 MHz.

Two physical channels exist in C-V2X; the Physical Sidelink Shared Channel (PSSCH) and Physical Sidelink Control Channel (PSCCH). The PSSCH carries the application data, also known as Transport Blocks (TBs). The PSCCH carries the Sidelink Control Information (SCI), which is critical for scheduling and decoding. The SCI contains information such as the Modulation and Coding Scheme (MCS) used to transmit the packet, the frequency resource location of the transmission, and other scheduling information.

The PSCCH and PSSCH can be transmitted using adjacent or non-adjacent schemes. In the adjacent scheme, the PSCCH and PSSCH are transmitted in contiguous RBs. In the non-adjacent scheme, the PSCCH and PSSCH are transmitted in different RB pools. In terms of occupancy, the PSCCH requires 2 RBs, while the number of RBs required by the PSSCH is variable and depends on the size of the TB. It is worth noting that the PSSCH and PSCCH are always transmitted in the same subframe independently of the transmission scheme.

3.2 C-V2X Medium Access Control Layer

At the MAC layer, C-V2X implements SB-SPS (Mode 4) to allow vehicles to select resources autonomously. The process starts with the reception of a packet from the upper layers. Upon reception, the MAC layer creates a scheduling grant containing the number of subchannels, the number of recurrent slots for which the subchannels will be reserved, and the periodicity between transmissions. If a grant has already been created at the time a packet is received from the upper layers, the transmission is scheduled using the existing grant. The number of subchannels is pre-configured and depends on the application requirements. The number of recurrent transmissions is defined by the Resource Reselection Counter (RRC), which is set by randomly selecting an integer value between 5 and 15. Finally, the periodicity between transmissions is defined by the Resource Reservation Interval (RRI), whose value is set by upper layers.

Once the grant is created, it is then passed to the PHY layer, which generates a list of all the subchannels meeting the grant specifications. These subchannels are known as Candidate Single-Subframe Resources (CSRs) and consist of one or multiple subchannels in the same subframe. The list contains all the CSRs within a selection window comprising the period between the time the packet is received from the upper layers and the maximum allowed latency.

The list is then filtered using the information in the SCIs received during a sensing window comprised of the last 1000 subframes. Based on this information, CSRs are excluded if the SCI indicates that it will be reserved during the upcoming selection window and if the average PSSCH Reference Signal Received Power (RSRP) of the CSR exceeds a predefined threshold. After excluding all CSRs that meet these two conditions, at least 20% of all the CSRs should remain available. Finally, the PHY selects the

20% of CSRs with the lowest Sidelink Reference Signal Strength Indicator (RSSI) averaged over the sensing window. This ensures the CSRs with the lowest levels of interference are considered for selection. The remaining CSRs are passed to the MAC layer, where a single CSR is selected at random to reduce the probability of multiple vehicles choosing the same CSR. The CSR is selected for a number of recurrent slots defined by the RRC, whose value is decreased by one after each transmission.

3.3 NR-V2X - Key Differences

Generally, 3GPP Rel. 16 NR-V2X Mode 2 maintains much the same approach as described for Mode 4. However some changes have been introduced at the PHY layer. This includes flexible numerology to allow for reduced sub-carrier spacing enabling low latency transmission. Additional channels have also been specified to enable groupcast and unicast communications which were not available for Mode 4. This introduces a multi-stage SCI format to enable these communication patterns. More information relating to NR-V2X PHY changes can be found in (Garcia et al., 2021).

At the MAC layer, we highlight only the changes that are significant with respect to impacting SB-SPS scheduling performance. The first relates to the RSRP filtering stage; rather than using an average RSRP value for the CSR in the sensing history as is the case in Mode 4, Mode 2 instead uses only the RSRP of the most recent transmission when determining reserved resources. The second key change is the outright removal of the RSSI filtering stage. As such, all CSRs not removed at the RSRP filtering stage will be reported to the MAC layer for selection. These modifications are important as shown in (Todisco et al., 2021), as they significantly impact the performance of SB-SPS when handling aperiodic traffic. Importantly, a dynamic grant scheduling mechanism is defined in 5G NR-V2X to deal with aperiodic traffic patterns. It operates by using the same underlying SB-SPS algorithm but assuming a single transmission. The SCI message for this transmission will highlight that the resource will not be maintained in the future. This does not apply when retransmissions are enabled, in which case a grant is maintained for said retransmissions. We do not consider retransmissions in this study.

4 RESULTS

In this section, the causative effects of declined SB-SPS performance when faced with aperiodic application traffic are quantitatively explored. We next investigate the limitations of the latest standardised approach to address this i.e. NR-V2X dynamic grants, when application traffic is highly aperiodic. Finally, we show that application traffic with hybrid periodic and aperiodic characteristics can perform adequately, motivating the need for a dedicated scheduling mechanism for highly aperiodic application traffic or a mechanism to allow aperiodic traffic to mimic periodic characteristics in order to minimise disruption to SB-SPS scheduling.

Table 1: Simulation Parameters.

Parameter	Value
Vehicular scenario	
Vehicular density (β)	0.12 veh/m & 0.3 veh/m
Highway length	2000 m
Number of lanes	3/6 in each direction (6/12 total)
Vehicle Speed	70km/h
Vehicle Mobility	SUMO (step-length = 1ms)
Channel settings	
Carrier frequency	5.9 GHz
Channel bandwidth	10 MHz
No. subchannels	3
Subchannel size	16 Resource Blocks
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

Results are based on the OpenCV2X[1] simulator (McCarthy and O'Driscoll, 2019) in conjunction with SUMO[2] (Lopez et al., 2018), and Artery[3] (Riebl et al., 2015). Table 1 describes the simulation parameters used. The vehicular scenario was chosen to comply with recommended 3GPP C-V2X simulation guidelines, specifically the "Highway Slow" scenario which has a density of 0.12 veh/m (3GPP, 2016)

[1] http://www.cs.ucc.ie/cv2x/
[2] https://sumo.dlr.de/docs/index.html
[3] http://artery.v2x-research.eu/

and adapted to the increased density of 0.3 veh/m. Packet sizes of 190B and bounded latency requirements within 100ms remain constant throughout all experiments. Application traffic is modelled as follows:

- **Periodic:** Vehicles transmit at a mean rate of 4Hz. This rate is deliberately chosen to allow for comparable analysis with the ETSI model with respect to channel load. Half of all vehicles transmit every 200ms with the remainder transmitting every 300ms, selection of 200ms or 300ms rate is done at random for each simulation.
- **Aperiodic (ETSI):** Literature often assumes a periodic CAM transmission rate. This does not align with the aperiodic transmission of CAMs according to the ETSI specification (ETSI, 2019a) where CAMs are triggered based on a vehicle's dynamics i.e. deviation in heading (>4°), position (>4m) and speed (>0.5m/s) or at 1s intervals if these conditions are not satisfied.

4.1 SB-SPS Performance for Aperiodic Traffic

We now quantitatively explore why SB-SPS exhibits declined performance when application traffic follows aperiodic arrival rates. Both C-V2X (Rel. 14) and NR-V2X (Rel. 16) are considered. The distinction between these, as described fully in Section 3.2, is that NR-V2X removes the RSSI filtering stage and only uses the RSRP of the most recent transmission when filtering candidate resources.

Ultimately, the results show that both SB-SPS standards exhibit declined performance when handling aperiodic traffic. This is due to inefficient resource use as a consequence of inaccurate knowledge, with the reasons differing depending on whether grant breaking is enabled or not. This leads to a rise in collisions and decreased packet delivery rates. Subsequent results prove this to be the case.

Table 2: Absolute number of colliding grants.

Scheduling Mechanism	γ_{TSim}
C-V2X (Periodic)	64
NR-V2X (Periodic)	20
C-V2X (ETSI GB)	4234
NR-V2X (ETSI GB)	1789
C-V2X (ETSI No-GB)	320
NR-V2X (ETSI No-GB)	86

Fig. 1 shows that SB-SPS with grant breaking (denoted as GB) performs worst for both NR-V2X and C-V2X. A grant break occurs as no TB exists to send

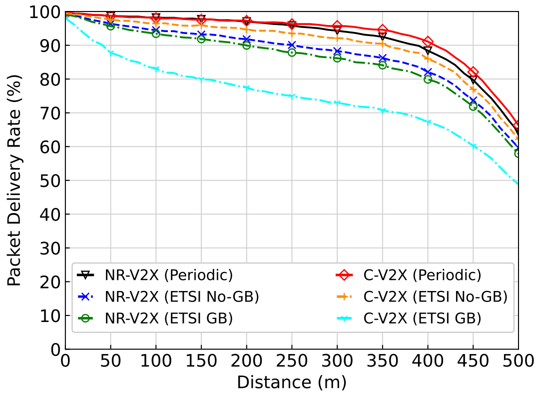


Figure 1: SB-SPS performance of NR-V2X (Mode 2) and C-V2X (Mode 4) for periodic and ETSI application models.β = 0.12 veh/m. With and without grant breaking.

in a scheduled slot, thus the resource goes unused as SB-SPS ends the grant when a missed transmission occurs. When vehicles frequently break their grants, they must schedule new resources. Each time resources are reserved there is a probability that a neighbouring vehicle will choose the same set of resources, particularly if inaccuracies are introduced to the sensing history. Furthermore, frequent grant breaking leads to under-utilisation of reserved resources which causes other vehicles to incorrectly consider increasingly small and similar resource pools. This increases the probability of vehicles choosing the same resources, which can be exacerbated further as vehicle density increases. This has a severe impact on C-V2X Mode 4 due to it's CSR selection mechanism incorporating RSSI filtering. In contrast, this stage is removed for NR-V2X which results in a larger CSR pool. This is shown by the γTSim metric in Table 2 which represents the number of instances where grants collide i.e. where neighbouring vehicles select the same subchannel in the same subframe for transmissions. It can be seen that C-V2X incurs a high number of colliding grants. While NR-V2X incurs less, for the reasons just outlined, it is still evident that grant breaking is incompatible with aperiodic traffic patterns.

Fig. 1 also shows NR-V2X and CV2X SB-SPS performance when grant breaking is disabled (denoted as No-GB). The grant is maintained irrespective of a missed transmission. It can be seen that while this greatly improves performance for C-V2X when compared to grant breaking, it still comes at a cost. Resources are reserved that may not be used. Furthermore these reserved but unused resources introduce inconsistencies in the CSR selection process where a vehicle does not send an SCI due to a missed transmission and neighbouring vehicles mistakenly believe the resource to be free for use. This can lead to collisions on future transmissions. What is particularly noteworthy is that NR-V2X performance when grant breaking is disabled is worse than the performance of C-V2X. This indicates that when the grant is maintained, RSSI filtering can be a positive feature by discouraging the selection of resources that exhibit high levels of interference. Furthermore, RSRP averaging can result in more accurate sensing history.

Irrespective of whether grant breaking is enabled or not, it has been shown that the performance of SB-SPS for NR-V2X and C-V2X becomes compromised due to inefficient resource scheduling. This leads to increased packet collisions as shown in Fig. 2.

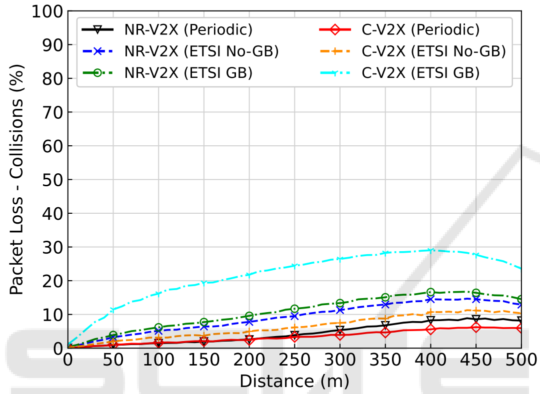


Figure 2: Packet collisions for periodic and ETSI application models. Vehicle density of 0.12 veh/m is considered.

4.2 NR-V2X Scheduling for Aperiodic Traffic

Having established why SB-SPS does not perform well for aperiodic ETSI traffic, we next investigate whether the NR-V2X Dynamic Grant mechanism proposed in Release 16 adequately addresses these limitations.

Fig. 3 shows the performance of dynamic grant versus NR-V2X SB-SPS for the ETSI aperiodic model. Disabled grant breaking is assumed. It is evident that at the lower density of 0.12 veh/m, the dynamic grant mechanism can marginally out-perform SB-SPS. However when the density increases to 0.3 veh/m, dynamic grant under performs SB-SPS. This is due to reliance on the SB-SPS sensing window. In the case of fully aperiodic application traffic such as ETSI, all TBs are scheduled using dynamic grant. As such all sensing history is irrelevant as no filtering will be done in the selection window. Ultimately this results in dynamic grant operating as a simple random selection mechanism where any resource in the selection window is equally likely to be selected. As such

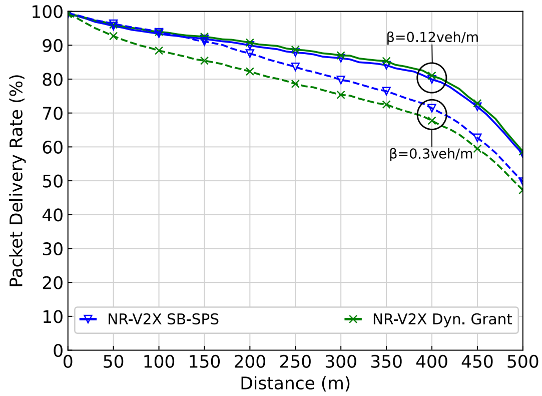


Figure 3: NR-V2X dynamic grant performance for fully aperiodic applications traffic. Vehicle densities of β=0.12 veh/m and β=0.3 veh/m are considered.

dynamic grant performs ineffectively in a fully aperiodic scenario.

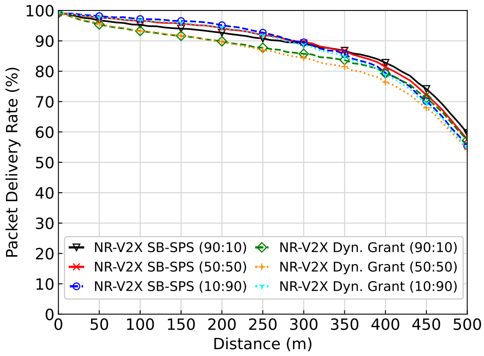
This is significant as ETSI and DENM messages which are fully aperiodic (ignoring retransmissions) are the basis for cooperative vehicular services, and it is widely envisaged that the messages associated with increased vehicle autonomy and cooperative sensing will also demonstrate highly aperiodic arrival rates. Given this, it highlights the need to either develop a dedicated scheduling mechanism to better handle traffic with aperiodic arrival rates or alternatively to ensure that application traffic mimics periodic arrivals in order for dynamic grant to function more effectively.

4.3 NR-V2X Scheduling for Hybrid Traffic

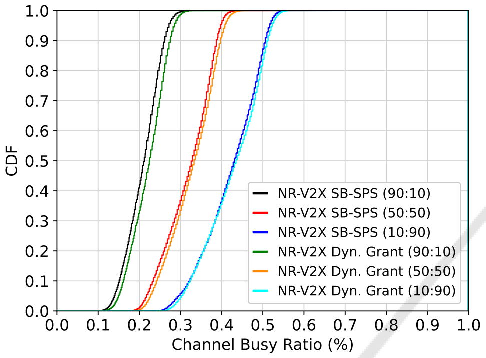
In the previous section, it was shown that the performance of NR-V2X dynamic grants is poor for fully aperiodic applications, particularly at higher densities. In this section, it is investigated whether dynamic grant can demonstrate improved performance if a proportion of the application traffic exhibits periodic characteristics, thereby leading to a more accurate SB-SPS sensing window.

Fig. 4a considers 3 hybrid application models:

- **(90:10):** 90% of the traffic follows an aperiodic arrival rate in line with ETSI vehicle dynamics with the remaining 10% representing periodic traffic with a 10Hz transmission rate.
- **(50:50):** This application model generates a 50:50 aperiodic/periodic arrival pattern.
- **(10:90):** 10% of traffic follows an aperiodic arrival rate as per ETSI, with 90% arriving periodically.



(a) NR-V2X PDR for SB-SPS & dynamic grant.



(b) NR-V2X CBR for SB-SPS & dynamic grant.

Figure 4: NR-V2X performance when considering hybrid aperiodic:periodic application models.

It is clear in Fig. 4a that the performance of dynamic grant for hybrid application models is actually worse than the performance of NR-V2X SB-SPS when assuming disabled grant breaking. There is a 5% decline in performance at almost all ranges for ratios up to 50%. Fig. 4b highlights a noteworthy aspect regarding performance; while CBR increases by over 10% as the models incorporate more periodic arrival rates, PDR performance doesn't change significantly. Indeed, the PDR performance is best for the highest CBR when the ratio is 90% periodic. Thus increasing the amount of periodic application traffic improves the performance of both these scheduling mechanisms as it reduces the overall number of collisions and more effectively utilises the SB-SPS sensing history. For the hybrid model with the highest level of periodic characteristics (10:90), the difference in PDR between the NR-V2X SB-SPS and Dynamic Grant is negligible.

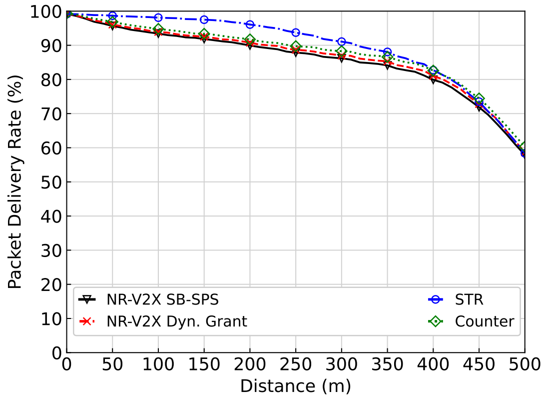
Ultimately it can be concluded that NR-V2X dynamic grant is not adequate when scheduling highly aperiodic traffic patterns. This motivates the study in the next sections, where alternative dedicated aperiodic schemes are implemented and quantitatively evaluated.

4.4 Alternative Dedicated Scheduling Mechanisms for Aperiodic Traffic

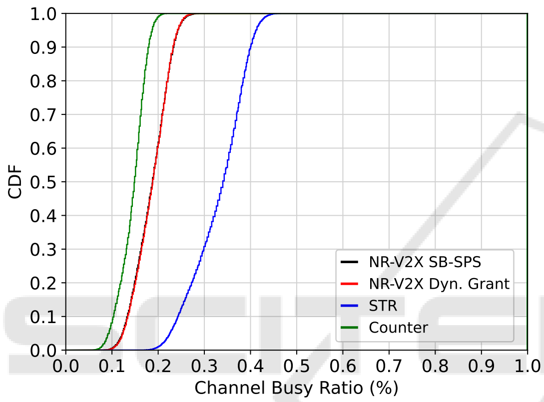
The results thus far have highlighted the limitations of NR-V2X dynamic grant in effectively accommodating fully aperiodic application traffic. One approach to address this would be to devise an entirely separate scheduling mechanism, independent of SB-SPS. Two mechanisms are next considered that were proposed as part of 3GPP working groups prior to Rel. 16. These have been incorporated into OpenCV2X but to the best of our knowledge have not been thoroughly quantitatively evaluated in literature. Their operation is briefly described:

- **Short-term Reservations (Labeled STR) (Ericsson, 2019):** Proposed by Ericsson, short-term reservations also referred to as short term sensing, makes use of two selection windows. It works by sending a reservation signal in the first selection window, which reserves resources in the second selection window on which to transmit the SCI and TB pair. In this mechanism, the resource on which to send the reservation signal is chosen randomly, discounting resources reserved for SCI and TB pairs. Until the reservation signal is sent, the vehicle continues to listen in case the reservation slot becomes reserved by another vehicle. At the time of sending the reservation signal, a future free resource is selected if it has not already been reserved in the second sensing window. This reduces contention for the transmission of SCI and TB pairs.
- **Counter based Mechanism (LG-Electronics, 2019):** This approach makes use of a simple counter to increase the randomness of the resource selection process. Upon receiving an application layer packet, a counter is randomly selected between $\{1, 40\}$. In each subframe, the counter is decremented by the number of free subchannels. Once the counter reaches 0, a free subchannel is chosen at random in the next available subframe where the SCI and TB pair will be transmitted.

It is clear from Fig. 5 that counter demonstrates negligible improvement over NR-V2X dynamic grant as it is essentially a random scheduling mechanism. STR demonstrates improved PDR but comes at the cost of significantly higher CBR as shown in Fig. 5b. This is attributable to the extra control overhead generated by reservation signals before SCIs and TBs are transmitted. This limitation would result in even worse performance at higher densities as the reservation signals would become a cause of collisions. While STR has limited for applicability for



(a) NR-V2X PDR when for SB-SPS, dynamic grant & dedicated aperiodic scheduling.



(b) NR-V2X CBR for SB-SPS, dynamic grant & dedicated aperiodic scheduling.

Figure 5: Dedicated aperiodic scheduling mechanisms.

ETSI CAMs, this approach could be applicable for high priority aperiodic traffic or traffic only generated sporadically such as DENMs.

5 CONCLUSIONS & DISCUSSION

This paper provides an in-depth study on the limitations of both C-V2X and NR-V2X SB-SPS algorithms in reliably supporting application traffic with aperiodic characteristics. It further provides important insights into the limitations of the NR-V2X dynamic grant scheduling mechanism, and is the first paper to do so while considering the Rel. 16 MAC with removed RSSI filtering and RSRP averaging. Ultimately it finds that neither approach is adequate for dealing with aperiodic traffic, either performing poorly or introducing inconsistencies into their scheduling decisions. Significantly, the performance of the NR-V2X standard under-performs C-V2X when dealing with fully aperiodic arrival rates due to the removal of RSSI filtering and RSRP averaging. Furthermore, dynamic grant performance has also been shown to be inadequate resembling random scheduling. It is shown that to perform adequately, dynamic grant must have a hybrid of periodic and aperiodic traffic to allow for accurate resource filtering. It should be noted that dynamic grant performance may improve with retransmissions although overhead may be prohibitive. Alternative dedicated aperiodic scheduling mechanisms were also explored but have their own drawbacks such as increased channel usage, which can limit their applicability.

Aperiodic traffic patterns are of vital importance as current and future communication patterns are and will continue to be aperiodic in nature e.g. cooperative awareness services based on CAMs, DENMs (ETSI, 2019b) and Cooperative Perception (ETSI, 2019c). These services will underpin vehicular communications and the current standards are not adequate to effectively manage these patterns. It is our conclusion that new approaches will need to be implemented to address this. This can be through the design of more effective dedicated aperiodic scheduling mechanisms which either work in conjunction with existing SB-SPS scheduling or as a standalone approach. Alternatively, and more promisingly, an approach that provides higher layer traffic shaping or more intelligent dynamic SB-SPS RRI selection would ensure that aperiodic traffic is scheduled similarly to periodic traffic, thus eliminating wasted resources and inconsistent sensing history. The authors in (Yoon and Kim, 2021) sought to address this, however the solution is based on an empirical data-set and cannot be generalised to predict application layer packet arrival. Such an approach would be effective for services such as cooperative awareness and perception which are frequently transmitted and based on vehicle/object dynamics that can be predicted, thus allowing SB-SPS to dynamically match this rate. Such an approach would allow frequently aperiodic traffic that forms the backbone of vehicular communications to mimic periodic arrival rates. Adopting such a mechanism would allow the NR-V2X dynamic grant to only be used for low frequency aperiodic traffic such as DENMs. This was shown in Fig. 4a to perform reliably. An investigation into the feasibility and performance of such a mechanism will form part of future work.

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REFERENCES

3GPP (Dec. 2020). Release 16 description; summary of rel-16 work items (v1.0.0 , release 16)). TR 21.916.

3GPP (Jul. 2016). Study on lte-based v2x services (v14.0.0, release 14). TR 36.885.

3GPP (Sep. 2019). Release 15 description; summary of rel-15 work items (v15.0.0 , release 15)). TR 21.915.

Bartoletti, S., Masini, B. M., Martinez, V., Sarris, I., and Bazzi, A. (2021). Impact of the Generation Interval on the Performance of Sidelink C-V2X Autonomous Mode. *IEEE Access*, 9:35121–35135.

Bazzi, A. (2019). Congestion control mechanisms in ieee 802.11p and sidelink c-v2x. In *2019 53rd Asilomar Conference on Signals, Systems, and Computers*, pages 1125–1130.

Ericsson (2019). *Resource allocation procedures for Mode 2*. 3GPP TSG RAN WG1 No.96 R1-1903166.

ETSI (April. 2019b). Etsi en 302 637-3; intelligent transport systems (its); vehicular communications; basic set of applications; part 3: Specifications of decentralized environmental notification basic service v1.3.1.

ETSI (April. 2019c). Etsi tr 103 562; intelligent transport systems (its); vehicular communications; basic set of applications; analysis of the collective perception service (cps); release 2 (v2.1.1).

ETSI (Jan. 2019a). En 302 637-2 intelligent transport systems (its); vehicular communications; basic set of applications; part 2: Specification of cooperative awareness basic service (v1.4.1).

Garcia, M. H. C., Molina-Galan, A., Boban, M., Gozalvez, J., Coll-Perales, B., Sahin, T., and Kousaridas, A. (2021). A Tutorial on 5G NR V2X Communications. *IEEE Communications Surveys & Tutorials*, page 1.

Gonzalez-Martín, M., Sepulcre, M., Molina-Masegosa, R., and Gozalvez, J. (2019). Analytical models of the performance of c-v2x mode 4 vehicular communications. *IEEE Transactions on Vehicular Technology*, 68(2):1155–1166.

LG-Electronics (2019). *Discussion on resource allocation mechanism for NR V2X*. 3GPP TSG RAN WG1 No.96 R1-1901933.

Lopez, P. A., Behrisch, M., Bieker-Walz, L., Erdmann, J., Flötteröd, Y.-P., Hilbrich, R., Lücken, L., Rummel, J., Wagner, P., and Wießner, E. (2018). Microscopic traffic simulation using sumo. In *The 21st IEEE International Conference on Intelligent Transportation Systems*. IEEE.

Lusvarghi, L. and Merani, M. L. (2020). On the Coexistence of Aperiodic and Periodic Traffic in Cellular Vehicle-to-Everything. *IEEE Access*, 8:207076–207088.

McCarthy, B. and O'Driscoll, A. (2019). Opencv2x mode 4: A simulation extension for cellular vehicular communication networks. In *2019 IEEE 24th International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD)*, pages 1–6.

Molina-Masegosa, R., Gozalvez, J., and Sepulcre, M. (2020). Comparison of ieee 802.11p and lte-v2x: An evaluation with periodic and aperiodic messages of constant and variable size. *IEEE Access*, 8:121526–121548.

Riebl, R., Gunther, H., Facchi, C., and Wolf, L. C. (2015). Artery: Extending veins for VANET applications. In *2015 International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS), Budapest, Hungary, June 3-5, 2015*, pages 450–456.

Romeo, F., Campolo, C., Molinaro, A., and Berthet, A. O. (2020a). Asynchronous traffic on the sidelink of 5g v2x. In *2020 IEEE International Conference on Communications Workshops (ICC Workshops)*, pages 1–6.

Romeo, F., Campolo, C., Molinaro, A., and Berthet, A. O. (2020b). Denm repetitions to enhance reliability of the autonomous mode in nr v2x sidelink. In *2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring)*, pages 1–5.

Todisco, V., Bartoletti, S., Campolo, C., Molinaro, A., Berthet, A. O., and Bazzi, A. (2021). Performance Analysis of Sidelink 5G-V2X Mode 2 through an Open-Source Simulator. *IEEE Access*, PP:1–1.

Yoon, Y. and Kim, H. (2021). A stochastic reservation scheme for aperiodic traffic in nr v2x communication. In *2021 IEEE Wireless Communications and Networking Conference (WCNC)*, pages 1–6.