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How does 5G NR V2X Mode 2 Handle Aperiodic Packets and Variable Packet Sizes?

Alejandro Molina-Galan[1], Baldomero Coll-Perales[1], Luca Lusvarghi[2,3], Javier Gozalvez[1], and Maria Luisa Merani[2,3]
[1]UWICORE laboratory, Universidad Miguel Hernández de Elche, Elche (Alicante), Spain.
[2]Dipartimento di Ingegneria Enzo Ferrari, Università degli Studi di Modena e Reggio Emilia, Italy.
[3]Consorzio Nazionale Interuniversitario per le Telecomunicazioni (CNIT), 43124 Parma, Italy
{alejandro.molinag, bcoll, j.gozalvez}@umh.es; {luca.lusvarghi5, marialuisa.merani}@unimore.it

***Abstract*—5G NR V2X complements LTE V2X to support advanced V2X services for connected and automated driving. 5G NR V2X introduces novel features at the MAC layer that are designed to cope with potential packet collisions, and that could help address the LTE V2X MAC inefficiencies observed under aperiodic traffic of variable size. This is the case of the re-evaluation mechanism that is a mandatory MAC feature of 5G NR V2X, and that seeks to avoid possible packet collisions detected before a vehicle transmits in selected resources. Evaluations conducted to date of 5G NR V2X do not consider the re-evaluation mechanism, and have focused on traffic patterns that do not fully account for the traffic variability of advanced V2X services. This paper extends the current state of the art with the first evaluation of a fully standard compliant 5G NR V2X implementation under the traffic patterns recommended by 3GPP for advanced V2X services. Our study shows that 5G NR V2X mode 2 still faces MAC challenges when using semi-persistent scheduling (SPS) to efficiently support aperiodic traffic of variable size.**

Keywords*—*5G NR V2X, Aperiodic traffic, CAV, C-V2X, cellular V2X, connected automated vehicles, eV2X, LTE V2X, Mode 2, packet collisions, re-evaluation, variable packet size.

I. Introduction

3GPP has published in Release 16 the 5G NR V2X standard that represents the first 5G NR (New Radio) release that supports sidelink (SL) or direct V2V (Vehicle-to-Vehicle) communications [1]. 5G NR V2X (or NR V2X) is designed to complement, and not replace, its predecessor V2X technology based on the LTE air interface, a.k.a. LTE V2X. The aim of LTE V2X is to support basic safety applications, relying on the exchange of broadcast messages among neighboring vehicles. NR V2X also allows unicast and groupcast communications, and introduces novel features and functionalities to support advanced services with stringent requirements. To this aim, NR V2X includes two novel operating modes: mode 1, where the cellular infrastructure is in charge of selecting the communication resources for every V2V communication, and mode 2, where vehicles autonomously communicate with no infrastructure support.

In this paper we focus on analyzing the efficiency of 5G NR V2X mode 2 to support advanced V2X services. These services are expected to generate V2X traffic patterns characterized by variable packet sizes and aperiodic generation times according to 3GPP [2]. The study in [3] evaluated the performance of LTE V2X mode 4 (the counterpart of NR V2X mode 2) under periodic and aperiodic traffic with fixed and variable packet sizes. [3] demonstrated that the MAC of LTE V2X mode 4 faces certain inefficiencies when vehicles generate aperiodic traffic of variable packet size that increase packet collisions.

NR V2X mode 2 can also operate using SPS scheduling with similar procedures as those present in LTE V2X mode 4 [1]. A key mandatory feature introduced in the MAC of NR V2X mode 2 (and that is not present in LTE V2X mode 4) is the re-evaluation mechanism that is designed with the objective of detecting and avoiding imminent packet collisions [4]. Previous studies have evaluated the performance of NR V2X mode 2 under different traffic patterns [5]-[8]. However, these studies do not implement the re-evaluation mechanism and do not consider the variability in both time generation and size of V2X packets as recommended in the 3GPP guidelines [2] that present models for the generation of packets for advanced V2X services. This is for example the case of the Cooperative Perception Service (CPS) that generates aperiodic messages with different sizes depending on the number of objects perceived by the sensors of the vehicle [9]. In this context, this paper complements the state of the art with the first evaluation of a fully standard compliant implementation of NR V2X mode 2 using SPS scheduling and the re-evaluation mechanism. The evaluation considers different traffic patterns including periodic and aperiodic traffic with fixed and variable packet sizes based on the models reported in the 3GPP guidelines [2]. To this aim, we have implemented an ns-3 simulator that is fully compliant with the 5G NR V2X mode 2 standard [4][10]. Our results show that NR V2X mode 2 also faces challenges to efficiently handle aperiodic packets of variable size with SPS scheduling despite its new MAC features. The rest of the paper is organized as follows: Section II gives an overview of NR V2X mode 2. Section III presents the simulation environment and Section IV the performance evaluation of NR V2X mode 2. Finally, Section V reports the main conclusions of this paper.

II. 5G NR V2X Mode 2

A. *Resource grid*

The resource grid of NR V2X is organized into slots in the time domain and Resource Blocks (RBs) in the frequency domain (Fig. 1). The slot duration and RB bandwidth depend on the utilized OFDM numerology (μ) or subcarrier spacing (SCS). 5G NR V2X supports a scalable SCS given by $2^{\mu} \times$ 15 kHz, where μ can be equal to 0, 1, 2, or 3. The slot duration is given by $2^{-\mu}$ ms and the RB consists of 12 consecutive subcarriers with the same SCS. All vehicles utilize the same SCS at a particular region. RBs are grouped into sub-channels (Fig. 1). A sub-channel is formed by RBs of the same slot. The sub-channel size (i.e., the number of RBs per sub-channel) can vary but it is common for all communicating vehicles. A sub-channel represents the smallest unit for a SL data transmission or reception. Data packets are transmitted in Transport Blocks (TB) that are carried in the Physical Sidelink Shared Channel (PSSCH). A TB can occupy one or several sub-channels depending on the packet size, the sub-channel size, and the utilized Modulation and Coding Scheme (MCS). In NR V2X, each TB is associated with a Sidelink Control Information (SCI) that indicates the resources used by the associated TB, as well as further information required for decoding the TB. The SCI in NR V2X is transmitted in two stages, and it is transmitted together with the TB in the same slot.

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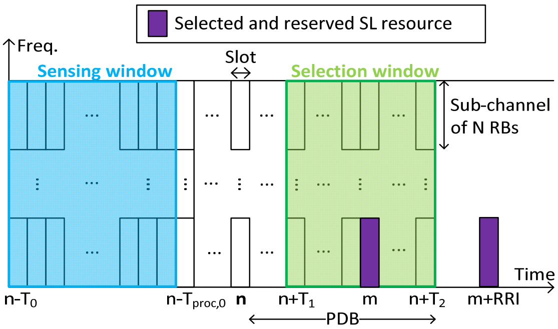


Fig. 1. NR V2X channelization and illustration of resource allocation mode 2 operation with SPS (when T_2 =PDB).

B. Resource Allocation

Mode 2 can operate using a dynamic scheme (DS) or a semi-persistent scheduling scheme (SPS). The DS selects new resources for each TB and can only reserve resources for the retransmissions of that TB. A vehicle can select and reserve resources for the transmission of several TBs when utilizing SPS. We should note that we distinguish in this work between a selected resource and a reserved resource. A reserved resource is a selected resource that a vehicle reserves for a future transmission by notifying neighboring vehicles using the SCI. Therefore, reserved resources provide stability to the operation of NR V2X mode 2. We focus on this paper on the SPS that, unlike DS, does not require the implementation of retransmissions to generate reserved resources.

SPS selects resources for a number of consecutive *Reselection Counter* TBs. The time period between the resources selected for the transmission of consecutive TBs is defined by the *Resource Reservation Interval* (*RRI*). The possible values of the *RRI* are {0, [1:1:99], 100:100:1000} ms. The *Reselection Counter* is randomly set within an interval that depends on the selected *RRI*. If *RRI*≥100 ms, this counter is randomly set within the interval [5,15]. If *RRI*<100 ms, the counter is randomly set within the interval[1] [5**C*,15**C*] where *C*=100/max(20,*RRI*) [4]. A vehicle initiates a new *Reselection Counter* when it selects new SL resources. A vehicle selects new SL resources when it generates a new TB and it does not have resources to perform the transmission that fits the size or latency requirements of the TB. The *Reselection Counter* is decremented by one after transmitting a TB. When *Reselection Counter* is depleted, the vehicle also selects new resources for the new TB with probability[2] (1-*P*).

To select new SL resources, a vehicle first defines the selection window where it looks for candidate resources to transmit a TB. The selection window includes all resources within the range of slots [$n+T_1$, $n+T_2$] (Fig. 1) [10], where *n* is the slot at which new resources must be selected. T_1 is the processing time (in slots) required by a vehicle to identify candidate resources and select new SL resources for transmission. The value of T_2 must be included within the range $T_{2min} \leq T_2 \leq$PDB, where PDB (Packet Delay Budget) is the latency deadline (in slots) by which the TB must be transmitted. Once the selection window is defined, the vehicle must identify the candidate resources within the selection window. A candidate resource is defined by a slot in time and *L* contiguous sub-channels in frequency. *L* must be selected such that the newly generated TB and its associated SCI fit in the candidate resource.

When a vehicle is not transmitting, it senses the SL resources during the sensing window that is defined in the range of slots [$n-T_0$, $n-T_{proc,0}$) (Fig. 1). T_0 defines the length of the sensing window and it can take values in slots equivalent to 100 ms or 1100 ms. $T_{proc,0}$ represents the number of slots required to complete the sensing procedure. During the sensing process, the vehicle uses the SCI received from other vehicles to determine which candidate resources from the selection window should be excluded. The vehicle also measures the RSRP of the transmissions associated with the SCIs received from other vehicles.

Mode 2 defines a 2-step algorithm to select new resources [10][4]. Step 1 excludes candidate resources in the selection window. The first exclusions relate to the half-duplex operation since a vehicle cannot sense reservations from other vehicles in the slots where it is transmitting. In this case, the vehicle excludes candidate resources of the selection window to avoid packet collisions with other vehicles that could send reservations in the slots of the sensing window where the vehicle was transmitting. Then, the vehicle excludes the candidate resources based on the reservations received from other vehicles in the SCIs during the sensing window. In this case, the candidate resources are only excluded if the measured RSRP is higher than a threshold. After executing all exclusions in step 1, the vehicle checks whether the percentage of remaining available candidate resources in the selection window is equal or higher than *X*%. If not, the RSRP threshold is increased by 3 dB, and step 1 is repeated again. In step 2, the vehicle randomly selects the SL resource for the transmission of the TB from the list of available candidate resources. A vehicle could optionally select up to 32 SL resources from the list of available candidate resources for the transmission and retransmissions of the TB.

The new re-evaluation mechanism introduced in NR V2X forces vehicles to check the availability of the selected resources. For example, a vehicle that has selected a SL resource at slot *m* must execute again step 1 at slot $m-T_3$ to check if the selected resource is still available (i.e., it is not excluded because another vehicle has reserved it). 3GPP defines this new execution of step 1 as re-evaluation check. The vehicle can optionally perform additional re-evaluation checks apart from the one executed at slot $m-T_3$. T_3 is the maximum time allowed for a vehicle (in slots) to complete the resource selection process. The re-evaluation check process works as follows. Consider *n'* in Fig. 2 as the slot at which a vehicle executes a re-evaluation check. The vehicle defines a new selection window SW' that starts at slot $n'+T_1$ and ends at slot $n'+T_2'$. T_2' must be within the range $T_{2min} \leq T_2' \leq$PDB-(n'-n). The vehicle executes then step 1 over the candidate resources in SW' in order to evaluate the currently available and excluded resources. If the selected resource at slot *m* is now excluded, then the vehicle has detected what is called in 3GPP standards a re-evaluation [10]. This re-evaluation detection triggers the execution of step 2 to select a new SL resource among the currently available resources in SW' [4] (Fig. 2)[3]. The vehicle does not execute step 2 if the initially selected resource remains available.

It is important to distinguish two cases where the vehicle executes a re-evaluation check. The first case happens when the vehicle has selected new SL resources in the selection window due to a reselection of resources (Fig. 2). We should note that the execution of a re-evaluation check is mandatory in this case according to the standard [4]. The second case occurs when the vehicle has not utilized a reservation announced in the SCI and it generates a new TB. Let us consider that the vehicle has not utilized a reservation at slot

[1] *C* is a constant to compute the *Reselection Counter* interval for *RRI* values lower than 100 ms.

[2] *P* is the probability to keep the same resources.

[3] The selection of new SL resources with re-evaluation does not imply that the vehicle initiates a new *Reselection Counter*.

$m+RRI$ and that it generates a TB at slot n_2, with $n_2 > m+RRI$. In this case, the vehicle could use a selected resource located at the slot $m+Y*RRI$, where Y is the minimum integer that fulfills $m+Y*RRI > n_2$, if $(m+Y*RRI - n_2) \leq PDB$. Since the resource located at $m+Y*RRI$ has not been reserved by the vehicle with a previous SCI, this resource is then considered a selected resource and it is up to UE implementation whether the vehicle also executes a re-evaluation check over it.

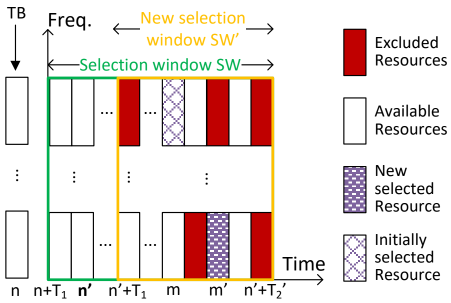


Fig. 2. Re-evaluation mechanism of NR V2X mode 2.

III. Simulation Environment

The evaluation of NR V2X mode 2 has been conducted using an in-house developed ns-3 simulator that implements NR V2X mode 2 following the 3GPP standard [10][4]. The evaluation considers the reference 3GPP highway scenario of 5 Km and 3 lanes in each driving direction [2]. The density of vehicles in the scenario varies between 25 and 100 veh/km, and we consider that the vehicle speed is 70 km/h. The vehicles transmit V2X packets following the periodic and aperiodic traffic models included in the 3GPP evaluation guidelines [2]. The periodic traffic model considers that 190-byte packets are generated with an inter-packet arrival time and latency requirement equal to {20, 100} ms. The 100 ms and 20 ms inter-packet arrival times are referred to as low and high traffic intensity scenarios by 3GPP. The aperiodic traffic model considers that the packets are generated with an inter-packet arrival time $\tau=c+r$, where c is a constant and r is an exponentially distributed random variable. The latency requirement of aperiodic traffic is set to c [2]. The low and high traffic intensity scenarios are modeled for aperiodic traffic considering that $c = \bar{r} = 50$ms and $c = \bar{r} = 10$ms, respectively. $\bar{r}$ is the mean of the exponential random variable. For the aperiodic traffic, the variable packet size is uniformly distributed in the [200,1200] byte range with a 200-byte step, while the fixed packet size is set to 200 bytes.

NR V2X mode 2 is configured to operate over a 20 MHz channel with a subcarrier spacing of 30 kHz in the 5.9 GHz frequency band. This channel bandwidth corresponds to 51 RBs. The sub-channel size is set to 12 RBs, which results in 4 sub-channels available in the channel. The transmission power has been set to 23dBm and the sensitivity has been set to -103.5dBm following [11]. The pathloss is modeled using the reference 3GPP models available in [2], and the shadowing effects are modeled using a log-normal distribution with zero mean and a standard deviation of 3dB [2]. Spatial shadowing correlation is also modeled following [2]. We consider that TBs are transmitted using the MCS index 13 with 16QAM modulation and coding rate equal to 0.5. With this MCS, packets of 190, 200, 400, 600, 800, 1000 and 1200 bytes are transmitted using 1, 1, 2, 3, 3, 4 and 4 sub-channels, respectively. Lookup tables from 3GPP working documents that relate the BLER (Block Error Rate)-SINR (Signal to Interference plus Noise Ratio) are used to model the transmissions of the TB [12] and SCI [13]. At the MAC layer, $T_{proc,0}$, T_0 and T_3 are set equal to 1 slot, 2200 slots and 5 slots respectively. The limits of the selection window T_1, T_{2min} and T_2 are set equal to 2 slots, 2 slots and PDB respectively. The PDB is set equal to the latency requirement of the traffic in number of slots. The percentage X of resources that must be available after the execution of step 1 in mode 2 is set to 20%, and the RSRP threshold that determines whether a resource is excluded or not is set to its minimum value (i.e. -128 dBm) following the results obtained in [6]. In addition, the probability P is set to 0 which indicates that a vehicle will always execute the 2-step SPS process when the *Reselection Counter* is depleted.

A key parameter for the operation of NR V2X mode 2 is the *RRI*. We evaluate two strategies for the *RRI* selection: average *RRI* and minimum *RRI*. These strategies set the *RRI* to the average and minimum inter-packet arrival time, respectively. Note that for periodic traffic the two *RRI* strategies result in the same *RRI* value. However, for aperiodic traffic, the average *RRI* strategy sets the *RRI* value to $c + \bar{r}$, while the minimum *RRI* strategy sets it to c.

Finally, we consider that vehicles execute a re-evaluation check at the slot that is mandatory by the standard (i.e. at slot m-T_3, where m is the slot where the resource was initially selected). We also consider that the vehicle executes a re-evaluation check in all selected resources, including the selected resource available after an unutilized reservation.

IV. Results

A. Metrics

We use the following metrics to evaluate the performance of NR V2X mode 2:

- Packet Delivery Ratio (PDR): fraction of correctly received TBs over the total number of transmitted TBs.
- Packet Collision Ratio (PCR): fraction of TBs that are incorrectly received due to packet collisions over the total number of transmitted TBs. This error occurs when the TB cannot be correctly decoded because the SINR is too low due to the interference generated by other vehicles.
- Size Reselection Ratio (SRR): fraction of TBs that produce a reselection due to the size of the TBs over the total number of transmitted TBs [3].
- Latency Reselection Ratio (LRR): fraction of TBs that produce a reselection due to the latency requirement of the TBs over the total number of transmitted TBs [3].
- Unutilized Reservation Ratio (URR): fraction of previously reserved resources that are not utilized for transmitting a TB over the total number of resource reservations. This metric does not account for unutilized reservations that are considered in the size and latency reselection ratios [3].
- Unused Sub-channels Ratio (USR): fraction of unused sub-channels in the resources used to transmit a TB over the total number of sub-channels that are in the resources used to transmit a TB [3].
- Reselection Counter Depletion Ratio (RCDR): fraction of Reselection Counters that deplete over the total number of initiated Reselection Counters.
- Re-evaluation Check Ratio (ReCR): fraction of TBs that are checked for re-evaluation at least once over the total number of transmitted TBs.
- Re-evaluation Detection Ratio (ReDR): fraction of TBs that experience at least one re-evaluation detection and trigger the selection of a new resource over the total number of transmitted TBs.
- Channel Busy Ratio (CBR): fraction of sub-channels that experience an RSSI higher than a threshold within an observation window of $100*2^{\mu}$ slots.

B. *Single traffic scenario*

We first analyze the impact of the V2X traffic characteristics on the operation and performance of the SPS scheduling scheme of NR V2X mode 2 considering that all vehicles in the scenario implement the same traffic pattern. Fig. 3 compares the PDR achieved by NR V2X mode 2 when vehicles transmit periodic traffic with fixed packet size and aperiodic traffic with fixed or variable packet size. Results are also reported in Fig. 3 for the two implemented *RRI* strategies that set the *RRI* value to the average and minimum inter-packet arrival time, and for the low (Fig. 3-left) and high (Fig. 3-right) traffic intensity scenarios that are characterized by average inter-packet arrival times of 100 ms and 20 ms, respectively. The CBR or channel load generated in each of these scenarios is shown in Table I. The results reported in Fig. 3 show that NR V2X mode 2 achieves a better PDR performance when vehicles generate packets periodically compared to the case when they generate packets aperiodically. The obtained results show that the differences in the PDR achieved by NR V2X mode 2 with periodic and aperiodic traffic increase with the vehicle density and traffic intensity (i.e., with the increasing CBR., Table I). For example, Fig. 3.a-left shows small PDR differences (below 2% when the distance between the transmitter and receiver is 300 m) between periodic traffic and aperiodic traffic with fixed packet size under the lowest evaluated vehicle density and traffic intensity. Under the highest evaluated vehicle density and traffic intensity, Fig. 3.b-right shows that the PDR of NR V2X mode 2 decreases by 36.3% for aperiodic traffic with fixed packet size with respect to periodic traffic when the distance between the transmitter and receiver is 300 m. It is important to note that this is the case despite the lower CBR values experienced for aperiodic traffic with fixed packet size with respect to periodic traffic[4] (see Table I).

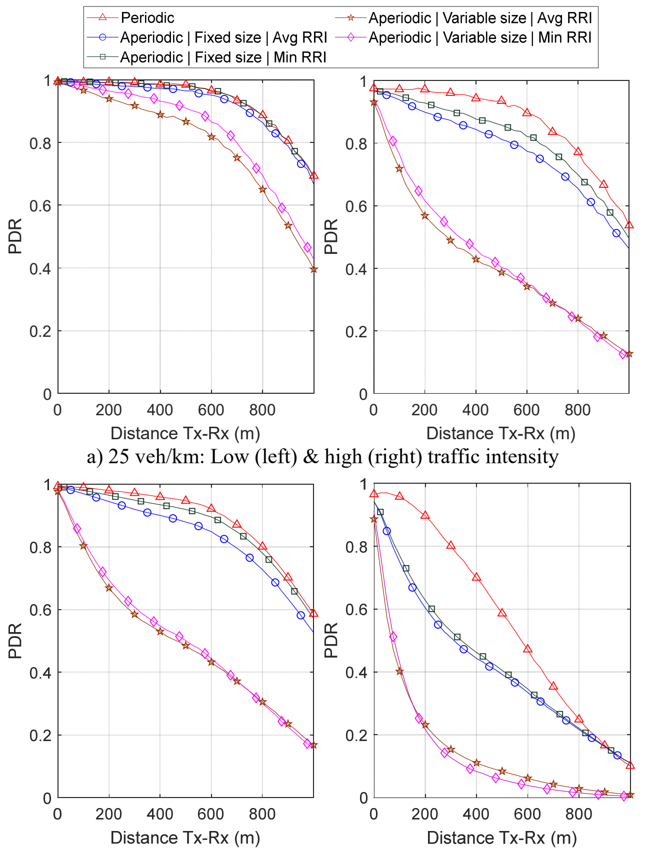
TABLE I. CBR (IN %) IN THE SINGLE TRAFFIC SCENARIO

Veh. Density (veh/km)	*Periodic*		*Aperiodic Fixed size*		*Aperiodic Variable Size*	
	Low	**High**	**Low**	**High**	**Low**	**High**
25	6	28	6	26	14	46
100	22	82	22	68	40	89

TABLE II. NR V2X OPERATION IN THE SINGLE TRAFFIC SCENARIO

RRI strategy	*Periodic*		*Aperiodic Fixed size*		*Aperiodic Variable Size*	
	Low	**High**	**Low**	**High**	**Low**	**High**
a) *Reselection Counter Depletion Ratio (RCDR) in %*						
Min RRI	100	100	83.9	10.8	44.2	5.5
Avg RRI			0.6	0	0.3	0
b) *Latency Reselection Ratio (LRR) in %*						
Min RRI	0	0	1	5	1	5
Avg RRI			55	58.1	55	57
c) *Size Reselection Ratio (SRR) in %*						
Min RRI	0	0	0	0	5	5
Avg RRI			0	0	26	27
d) *Unutilized Reservation Ratio (URR) in %*						
Min RRI	0	0	60	59	56	57
Avg RRI			6	6	4	4
e) *Unused Sub-channels Ratio (USR) in %*						
Min RRI	0	0	0	0	29	29
Avg RRI			0	0	27	27

Table II reports a set of key metrics that show that the SPS scheduling scheme of NR V2X mode 2 achieves better performance under the presence of periodic traffic than aperiodic traffic. This is for example shown by means of the RCDR (Table II.a)) that is 100% when vehicles generate packets periodically. Achieving an RCDR equal to 100% indicates that vehicles always deplete their *Reselection*



a) 25 veh/km: Low (left) & high (right) traffic intensity

b) 100 veh/km: Low (left) & high (right) traffic intensity

Fig. 3. Packet Delivery Ratio (PDR) in the single traffic scenario.

Counter reservations to perform the transmissions of their packets (or TBs) without executing additional resource reselections. This behavior brings significant stability to the operation of NR V2X mode 2 with SPS that results in the better PDR performance reported in Fig. 3. Table II.a) also shows that the RCDR is below 100% for the aperiodic traffic patterns. For example, for the case of aperiodic traffic with fixed packet size, the variations in the time between packets can cause additional resource reselections before the *Reselection Counter* depletes. These are referred to as latency reselections and are computed by means of the LRR in Table II.b). As it is shown in Table II.b), the chosen *RRI* strategy highly impacts the LRR generated by aperiodic traffic. When the average *RRI* strategy is implemented, more than 50% of the packets trigger a resource reselection, and therefore the *Reselection Counter* is very seldomly depleted (see Table II.a)). The higher number of resource reselections makes the SPS scheduling scheme of NR V2X mode 2 more unstable and likely to provoke packet collisions. This is the case because with the increasing number of resource reselections it is more likely that there are several vehicles selecting new resources around the same time (i.e., with their selection windows overlapping), and that they end up choosing the same ones. The minimum *RRI* strategy significantly reduces the LRR compared to the average *RRI* strategy (see Table II.b)[5], which results in the higher RCDR levels reported in Table II.a). The different RCDR levels experienced by the minimum *RRI* strategy under aperiodic traffic with fixed packet size in the scenarios with low and high traffic intensity (i.e., 84% vs 11%) are due to the different ranges for selecting the *Reselection Counter* when the *RRI* is set to 50 ms (low

[4] Periodic and aperiodic traffic with fixed packet size generate on average the same number of packets. The lower CBR values measured for aperiodic traffic in Table I are due to its higher packet collisions (see Fig. 4).

[5] The latency reselections with minimum RRI only occur in a corner case where the new TB to be transmitted is generated in the middle of a slot where a reservation is located.

traffic intensity) and 10 ms (high traffic intensity). As it is described in Section II, the resulting ranges are [10, 30] and [25, 75], respectively, which makes more likely to deplete the *Reselection Counter* when the *RRI* is set to 50 ms. However, the side effect of utilizing the minimum *RRI* strategy are the higher values of unutilized reservations measured by the URR (Table II.d)). The unutilized reservations can also negatively impact the operation of the SPS scheduling scheme of NR V2X mode 2. This is the case because unutilized reservations are discarded by the vehicles as part of step 1 of the SPS scheduling scheme (see Section II), although at the end they are not going to hold the transmission of a TB. This reduces the number of available candidate resources over which vehicles randomly select from during the execution of step 2 of SPS (see Section II). Therefore, the likelihood that two vehicles end up selecting the same resources increases. The operation of NR V2X mode 2 under aperiodic traffic with fixed packet size when implementing the average and minimum *RRI* strategies has shown some trade-offs in terms of RCDR, LRR, and URR. The results reported in Fig. 3 show that these trade-offs compensate each other and only a slightly higher PDR is achieved when NR V2X mode 2 is configured with the minimum *RRI* strategy.

Fig. 3 shows that NR V2X mode 2 sees its PDR degrade when vehicles generate aperiodic traffic with variable packet size. Aperiodic traffic with variable packet sizes challenges the operation of SPS of NR V2X mode 2. In particular, aperiodic traffic with variable packet size experiences not only the latency reselections and unutilized reservations that aperiodic traffic is prone to (see Table II). The variable packet sizes also produce additional resource reselections when the new generated TB does not fit in the previously reserved or selected resource. These reselections are referred to as size reselections and are computed in Table II.c) by means of the SRR. Size reselections represent an additional source of instability for the operation of NR V2X mode 2 that is reflected in the reduction (~50%) of the RCDR (Table II.a)) and PDR (Fig. 3) with respect to aperiodic traffic with fixed packet size. Table II.c) shows that the implemented *RRI* strategy also impacts the SRR. In particular, the obtained results show a significant reduction (~80%) in the SRR when NR V2X mode 2 is configured with the minimum *RRI* strategy with respect to the average *RRI* strategy. This is the case because with the minimum *RRI* strategy, the resource reselections not caused by the depletion of the *Reselection Counter* are almost limited to size reselections. Size reselection triggered to accommodate a TB that occupies more sub-channels than the reserved ones can also be used to transmit upcoming TBs of equal or smaller sizes. This is at the cost of leaving some sub-channels unused (see Table II.e)) that other vehicles cannot utilize since they are reserved. The increasing USR has also a negative impact on the operation of SPS of NR V2X mode 2 because it reduces the availability of candidate resources and therefore increases the risks of packet collisions. With the average *RRI* strategy, the additional latency reselections result in that the selected/reserved resources are fitted more often to the size of the new generated packets. Then, size reselections need to be triggered when forthcoming packets request additional sub-channels than the ones previously reserved in the latency reselection. Like it has been shown above for aperiodic traffic with fixed packet size, there exist different trade-offs with aperiodic traffic with variable packet size that impact the operation of the NR V2X mode 2 when it is configured with the minimum or average *RRI* strategies. In this case, results reported in Fig. 3 show that these trade-offs also compensate each other, and only slight differences in the PDR are achieved when NR V2X mode 2 is configured with the minimum *RRI* or average *RRI* strategy.

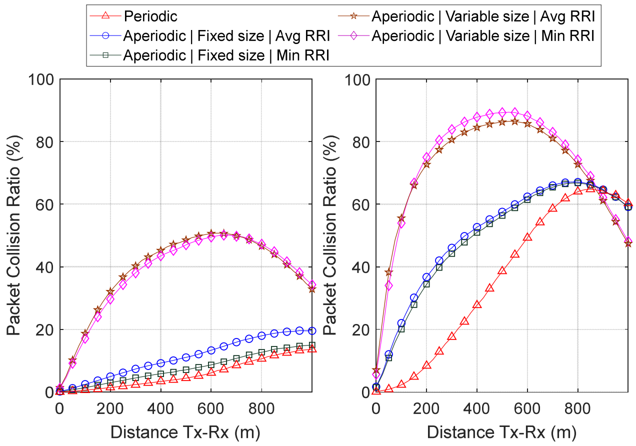


Fig. 4. Packet Collision Ratio (PCR) under low (left) & high (right) traffic intensity; 100 veh/km – similar trends observed for other vehicle densities.

The analysis performed above has highlighted the challenges that NR V2X mode 2 faces to efficiently support aperiodic traffic with fixed and variable packet sizes. The analysis is revealing that these challenges end up making the SPS scheduling scheme of NR V2X mode 2 more unstable with the potential risk of causing additional packet collisions. Fig. 4 reports the Packet Collision Ratio (PCR) as a function of the distance between the transmitter and the receiver for all the evaluated traffic patterns and *RRI* strategies when the vehicle density is 100 veh/km. The results reported in Fig. 4 help identifying that the degradation in PDR between the scenarios with periodic and aperiodic traffic (Fig. 3) is due to higher packet collisions experienced with aperiodic traffic. For example, Fig. 4 shows that aperiodic traffic with variable packet size increases the PCR from 2.3% to 38% and from 17.6% to 83.9% with respect to periodic traffic under low and high traffic intensity when the distance between the transmitter and the receiver is 300 m.

As it was demonstrated in [3], LTE V2X mode 4 shows similar inefficiencies and high PCR figures when transmitting aperiodic traffic with variable packet size. NR V2X mode 2 faces similar challenges despite introducing the re-evaluation mechanism originally designed with the objective to reduce the packet collisions. We measure the operation of re-evaluation in terms of the re-evaluation check (ReCR) and detection (ReDR) ratios that indicate the fraction of TBs that are eligible to be re-evaluated and those over which the re-evaluation is actually detected because a potential collision is identified, respectively. It is important to recall that only TBs that are to be transmitted in a selected resource (i.e., not reserved) are eligible for the re-evaluation check. The reselections that occur when transmitting aperiodic packets (because of the size and latency reselections, see Table II) result in ReCR levels between 50% and 70% independently of the vehicle density. The ReDR experiences levels up to 30%. Higher ReDR levels are measured with increasing vehicle densities because of the higher CBR and thus likelihood that two vehicles select the same resources. The observed ReDR levels show that re-evaluation is active. However, the results reported in Fig. 4 show that it is not effective as NR V2X mode 2 still experiences high PCR levels when transmitting aperiodic traffic. Fig. 4 questions the impact of re-evaluation on the performance of NR V2X mode 2 when transmitting aperiodic packets. For example, when aperiodic traffic with variable packet size is transmitted, NR V2X mode 2 configured with the minimum *RRI* strategy experiences an ReDR level of ~30%, while this level reduces to 2.5% (low traffic intensity) and to 7.5% (high traffic intensity) for the average *RRI* strategy. In spite of these ReDR differences, both strategies experience similar PCR levels. The obtained results show that even although re-evaluation is avoiding the detected collisions for a non-negligible percentage of TBs, it is not capable of counteracting the high packet collisions caused by the instability that aperiodic traffic is introducing in the operation of the SPS scheduling scheme of NR V2X mode 2.

C. Mixed traffic scenario

Finally, we analyze the operation of NR V2X mode 2 in a more realistic scenario where vehicles generate traffic with different patterns. In particular, we consider that 80% and 20% of the vehicles in the scenario implement the low and high traffic intensity models characterized by 100 ms and 20 ms average inter-packet arrival times, respectively. These mixed traffic intensities result in the CBR levels reported in Table III which are in line with the weighted values of the low and high traffic intensity ones reported in Table I. The PDR differences observed in the mixed traffic scenario between periodic and aperiodic traffic (Fig. 5-left) are again due to the higher PCR values experienced by aperiodic traffic (Fig. 5-right).

It should be noted that these high PCR values are experienced by aperiodic traffic in the mixed traffic scenario in spite of the increased ReDR levels with respect to the single traffic scenario. For example, the ReDR levels increase from 30% (low and high traffic intensity) in the single traffic scenario to 44.6% in the mixed scenario when transmitting aperiodic packets with variable size and using the minimum *RRI* strategy. The ReDR levels increase from 2.5% (low traffic intensity) or 7.5% (high traffic intensity) in the single traffic scenario to 16% in the mixed traffic scenario when transmitting aperiodic packets with variable size and using the average *RRI* strategy. However, despite the increase in the ReDR, we can observe similar trends in the PCR reported in Fig. 5-right to those reported in Fig. 4.

TABLE III. CBR (IN %) IN THE MIXED TRAFFIC SCENARIO

Veh. Density (veh/km)	*Periodic*	*Aperiodic Fixed size*	*Aperiodic Variable Size*
25	11	10	23
100	38	35	62

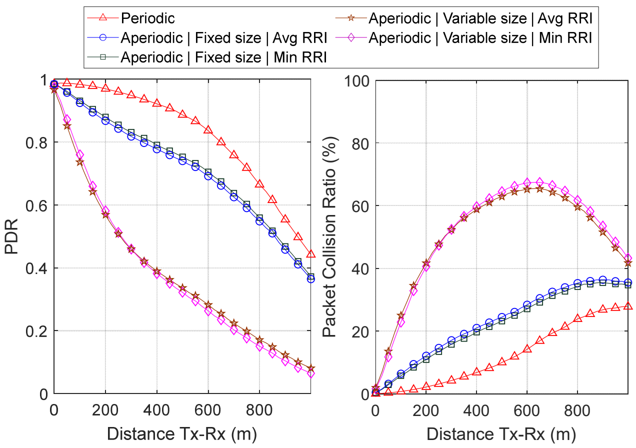


Fig. 5. Packet Delivery Ratio (PDR) -left- and Packet Collision Ratio (PCR) -right- for the mixed scenario (100 veh/km - similar trends observed for other vehicle densities).

V. CONCLUSIONS

This paper has presented the first fully standard compliant evaluation of 5G NR V2X mode 2 with SPS scheduling under periodic and aperiodic traffic of fixed and variable packet size in accordance with the 3GPP traffic model recommendations. The configuration of NR V2X mode 2 has considered two strategies that set the *RRI* to the minimum or to the average inter-packet arrival times. Both strategies result in multiple trade-offs, but none reduces the resource management instability of 5G NR V2X mode 2 observed when transmitting aperiodic traffic with variable packet size using SPS. These instabilities reduce the PDR and increase packet collisions with respect to scenarios where vehicles generate packets periodically. The obtained results present similar trends as those observed with LTE V2X mode 4 when transmitting aperiodic traffic, despite the new and mandatory re-evaluation mechanism of 5G NR V2X mode 2 that identifies and avoids possible packet collisions. These results call for further improvements to the MAC of 5G NR V2X mode 2 in order to efficiently handle variability in packet generation and size. An option that has been discussed is adapting the MCS to reduce size reselections triggered when the generated TB does not fit in the reserved resources. However, this is not exempt from challenges since the objective of adapting the MCS (a.k.a. link adaptation) is to adapt the error protection (and data in a packet) as a function of the link quality. Adapting the MCS to avoid size reselections could compromise the correct reception of the TB based on the link quality, and requires a careful study and design.

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