# A Selective Re-Evaluation Mechanism for 5G NR V2X Mode 2 Communications

Alejandro Molina-Galan, *Student Member, IEEE*, Javier Gozalvez, *Senior Member, IEEE*, Baldomero Coll-Perales, *Member, IEEE*

***Abstract*—The Internet of Vehicles (IoV) vision requires the pervasive capacity of connected and automated vehicles to communicate with their driving environment. To this aim, direct or sidelink Vehicle-to-Everything (V2X) communications should complement network-based communications with reliable and low latency local connectivity. 5G NR V2X has been designed to support advanced V2X services for connected and automated driving. These services can generate aperiodic traffic of variable size that can cause packet collisions when vehicles autonomously select their radio resources under 5G NR V2X mode 2. To prevent such collisions, the standard introduces a re-evaluation mechanism that vehicles use to detect and avoid packet collisions prior to their transmission on selected resources. This study first shows that re-evaluation is not fully effective in avoiding packet collisions because many of the detected collisions ultimately do not happen under the presence of aperiodic traffic of variable size, and selecting new resources increases the probability of packet collisions. To address these challenges, we propose a selective re-evaluation mechanism that changes resources only when the vehicle is certain that a collision detected with re-evaluation will occur, which is the case when a re-evaluation detection is triggered by a reservation for a retransmission of a TB. This study shows that the proposed selective re-evaluation mechanism improves the reliability and latency of 5G NR V2X mode 2 communications.**

***Index Terms*—5G NR V2X, NR V2X, mode 2, re-evaluation, CAV, connected and automated driving, V2V, collisions, resource allocation, reliability, latency, Internet of Vehicles.**

## I. INTRODUCTION

Pervasive connectivity is fundamental to realize the vision of an Internet of Vehicles (IoV) where connected and automated vehicles can communicate with each other and their surrounding environment. To this aim, conventional network-based communications should be complemented with direct or sidelink (SL) Vehicle-to-Everything (V2X) communications. The 3GPP 5G NR V2X (or NR V2X) standard supports direct or sidelink Vehicle-to-Vehicle (V2V) or Vehicle-to-Infrastructure (V2I) communications, and complements LTE V2X designed for basic awareness V2X services [1]. NR V2X introduces new features at the MAC and PHY layers to support advanced V2X (eV2X) services for connected and automated driving [2][3]. These services can generate aperiodic packets of variable (and larger) size [4], and have more stringent requirements, e.g. in terms of latency and reliability [5]. The standard defines two operating modes. In mode 1, the cellular infrastructure selects and manages the radio resources for SL communications. In mode 2, vehicles autonomously select and manage the resources without the support of the cellular infrastructure. This study focuses on NR V2X mode 2 since it ensures that V2X service provisioning is not limited by cellular coverage.

NR V2X inherits from LTE V2X the sensing-based scheduling scheme. However, it introduces an important novelty at the MAC layer, a re-evaluation mechanism designed to detect and avoid packet collisions. Several studies have recently studied the impact of packet collisions in C-V2X communications and possible countermeasures. A recent study [6] improves the performance of NR V2X mode 2 with periodic traffic by prioritizing the selection and reuse of resources reserved by other vehicles located beyond a specified threshold distance when there are few available resources. Similarly, the study in [7] improves the performance of LTE V2X with a resource allocation that assigns the same radio resources to vehicles separated by a distance threshold. The proposal uses the localization of vehicles and is only applicable when the cellular infrastructure manages the allocation of radio resources. In [8], the authors demonstrate that the performance of LTE V2X degrades in a scenario where a portion of vehicles transmits aperiodic traffic and the other portion transmits periodic traffic compared to a scenario where all vehicles transmit periodic traffic. In [9], the authors evaluate different schemes to mitigate the reciprocal interference that can be caused by NR V2X and IEEE 802.11p when both standards operate in the same channel.

Most NR V2X mode 2 studies do not implement the re-evaluation mechanism despite being a mandatory MAC feature [10] to address packet collisions, which are particularly present with aperiodic traffic of variable size [11]. With re-evaluation, a vehicle checks before transmitting the next packet if its selected resources are still available. If the re-evaluation mechanism detects that the selected resources have been reserved by another vehicle, the vehicle selects new resources

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The authors are with the UWICORE Laboratory, Universidad Miguel Hernandez de Elche (UMH), 03202 Elche, Spain, e-mail: {alejandro.molinag, j.gozalvez, bcoll}@umh.es.

to prevent a possible packet collision [10]. In [12], the authors conducted an in-depth simulation-based analysis of the standard re-evaluation mechanism in NR V2X mode 2. The study demonstrates that re-evaluation is effective with periodic traffic of fixed size, but loses effectiveness under aperiodic traffic of variable size, which increases packet collisions. The conducted analysis shows that re-evaluation is not fully effective in avoiding packet collisions generated by aperiodic traffic of variable size because many of the detected collisions ultimately do not happen (due to size or latency reselections and unutilized reservations) and selecting new resources increases the probability of packet collisions. However, [12] does not provide a solution for the inefficiencies NR V2X mode 2 faces when transmitting aperiodic packets of variable size. In contrast, this paper addresses these inefficiencies, and advances the state of the art with a novel selective re-evaluation mechanism that improves the reliability and latency of 5G NR V2X mode 2 communications, in particular under the presence of aperiodic traffic of variable size. To do so, the proposed selective re-evaluation mechanism only selects new resources when the vehicle is certain that a detected collision is going to occur, which is the case when a re-evaluation detection is triggered by a reservation for a retransmission of a TB. This study shows that the proposed selective re-evaluation mechanism improves the reliability and latency of 5G NR V2X mode 2 communications. In addition, the study includes new analytical models derived to characterize and understand the operation of NR V2X mode 2, which have been relevant to design the selective re-evaluation proposal.

The paper is organized as follows. Sections II and III provide an overview of 5G NR V2X mode 2 and the standard re-evaluation mechanism. Section IV analytically quantifies the effectiveness of the standard re-evaluation mechanism. Section V describes the proposed selective re-evaluation mechanism. Sections VI and VII detail the simulation environment and the evaluation of 5G NR V2X mode 2 using both the standard and selective re-evaluation mechanisms. Lastly, Section VIII summarizes the main outcomes of this study.

## II. 5G NR V2X Mode 2

NR V2X organizes the radio resources into slots in the time domain and Resource Blocks (RBs) in the frequency domain (Fig. 1). NR V2X supports a flexible subcarrier spacing (SCS) configured by the OFDM numerology ($\mu$), but all vehicles must utilize the same SCS under mode 2 within a given area. $\mu$ can be equal to 0, 1, 2 or 3, and the SCS is equal to $2^{\mu}$x15 kHz. The SCS determines the slot duration (equal to $2^{-\mu}$ ms) and the RB bandwidth (equal to 12*SCS kHz). RBs are grouped into sub-channels (Fig. 1), and the number of grouped RBs determine the sub-channel size. Vehicles transmit data packets in Transport Blocks (TBs). The number of sub-channels utilized for each TB depends on the packet size, the sub-channel size, as well as the Modulation and Coding Scheme (MCS). In NR V2X, each TB has an associated Sidelink Control Information (SCI) that is transmitted in the same slot as the TB. The SCI provides information on the sub-channels used by the TB, and information necessary for decoding the TB. The SCI can also indicate the reservation of resources for future TBs and retransmissions of the associated TB.

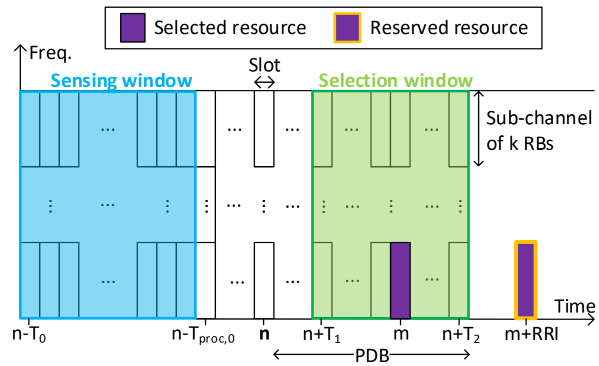



Fig. 1. NR V2X channelization and illustration of the resource allocation in mode 2 with SPS ($T_2$=PDB).

### A. *Resource allocation*

NR V2X mode 2 includes dynamic scheduling (DS) and semi-persistent scheduling (SPS) schemes. The DS scheme selects and reserves resources for a single TB, whereas the SPS scheme selects and reserves resources for the transmission and possible retransmissions of multiple consecutive TBs. We should highlight the important difference between a reserved and a selected resource. A reserved resource is a selected resource whose reservation has been announced with the transmission of a previous TB and its associated SCI. Selected resources are the ones a vehicle uses to transmit the first TB after selecting new resources or after a reservation goes unused. Selected resources are hence not reserved. This paper focuses on the SPS scheme since aperiodic transmissions of variable size mostly affect SPS as DS selects and reserves new resources for each TB. The effectiveness of re-evaluation is then particularly relevant when utilizing the SPS scheme.

With SPS, a vehicle that must select new resources to transmit a TB first defines the selection window (SW) that includes every resource within the range of slots [$n+T_1$, $n+T_2$] (Fig. 1). $n$ is the slot where the vehicle generates the TB and selects new resources. $T_1$ is the processing time (in slots) needed by a vehicle to select new resources. The vehicle sets the value of $T_2$ within $T_{2min} \leq T_2 \leq$PDB, where PDB is the Packet Delay Budget or latency requirement to transmit a TB. The vehicle then identifies all candidate resources within the selection window. A candidate resource must include $K_{SCH}$ adjacent sub-channels within a slot that fit both the TB and SCI to be transmitted.

To select new resources among the identified candidate resources, SPS defines a sensing window within the range of slots [$n$-$T_0$, $n$-$T_{proc,0}$) (Fig. 1) [13]. $T_0$ can be equal to 100*$2^{\mu}$ or 1100*$2^{\mu}$ slots, while $T_{proc,0}$ can take values from 1 to 4 slots depending on the SCS. During [$n$-$T_0$, $n$-$T_{proc,0}$), vehicles decode the SCIs sent by neighboring vehicles to identify the resources they reserved for their following transmissions. The vehicles also measure the Reference Signal Received Power (RSRP) of the TBs associated with the decoded SCIs [14].

The vehicle that must select new resources to transmit a TB uses then a two-step algorithm to select the resources [10][13]. In step 1, the vehicle excludes candidate resources from the selection window if: 1) they have already been reserved by other vehicles (through their SCIs), and 2) the measured RSRP exceeds a pre-defined RSRP threshold. If the percentage of remaining available candidate resources in the selection window is below a threshold, the RSRP threshold is increased by 3dB and the vehicle repeats step 1 [13]. In step 2, the vehicle randomly selects $N$ available candidate resources ($N \leq 32$) for the initial transmission of a TB and its $N$-$1$ retransmissions[1]. If $N>1$, the vehicle selects the $N$ candidate resources so that all retransmissions of the TB can be reserved by the initial transmission or a previous retransmission of the TB. To do so, the vehicle selects the first candidate resource randomly. For the following ones, the vehicle must consider that an SCI can only reserve a maximum of 2 candidate resources for retransmissions of the TB [10], and the SCI can only reserve resources for retransmissions that take place up to 31 slots later than the SCI [13].

With SPS, a vehicle that must select new resources, selects them for the transmission of *Reselection Counter (RC)* consecutive TBs. The time period between the selected resources for consecutive TBs is the *Resource Reservation Interval* (*RRI*). The *RRI* is included in the SCI in order to reserve resources for the transmission of a new TB. The vehicle decrements by one the *RC* every time it transmits a TB and its $N$-1 retransmissions. When *RC* is equal to zero, the vehicle selects new resources with probability (1-$P_k$) to transmit its following TBs; $P_k$ is the probability of keeping the same selected resources and can be configured between 0 and 0.8. If a vehicle must select new resources when *RC* is depleted, it informs other vehicles using the SCI that it will not be using anymore the same resources.

### B. Traffic variability

A vehicle may have to select new resources even if *RC* is not depleted. This occurs if a new TB does not fit the size of the reserved resources, or if the PDB of the new TB cannot be satisfied with the reserved resources. We refer to these MAC events as *size reselection* and *latency reselection* respectively [15]. Size reselections can occur when vehicles generate TBs of variable size. When vehicles select and reserve resources, they select and reserve them considering the size of the TB generated at the time when they select new resources since they cannot anticipate the size of the following TBs. If any of these following TBs has a larger size and does not fit in the reserved resources, the vehicle must drop the current reservation and select new resources for the new TB. Similarly, latency reselections can occur when vehicles aperiodically generate TBs. When a vehicle reserves resources, it reserves them at every *RRI* slots from the first selected resource for the following TBs. If any of these reserved resources do not comply with the latency requirement or PDB of any of these following TBs then a latency reselection occurs. The vehicle would then need to drop the current reservation and select new resources that comply with the PDB of the new TB. We should note that, in case of a size or latency reselection, the vehicle cannot notify other vehicles that it will not use the reserved resources for the following TB since reselections cannot be anticipated.

[1] NR V2X supports blind and Hybrid Automatic Repeat Request (HARQ) feedback-based retransmissions. We consider blind retransmissions when referring to retransmissions in this paper.

It is also possible in case of aperiodic traffic that a vehicle has resources reserved at, for example, slot $s_t$, but the following TB is generated after $s_t$. In this case, the vehicle can use the selected resources at $s_t$+*RRI* to transmit the new TB. However, the transmission at $s_t$+*RRI* is prone to packet collisions since the vehicle did not transmit any TB at $s_t$ and hence could not reserve the resources at $s_t$+*RRI*. We refer to this condition as *unutilized reservation* [15]. A vehicle cannot anticipate an unutilized reservation, and hence cannot notify other vehicles that it will not use the resources at $s_t$. We should note that size and latency reselections also generate reservations that are not utilized when they drop their current reservation because the TB to be transmitted does not fit the reserved resources or the current reservation does not comply with the latency requirement or PDB of the TB to be transmitted. We should also note that the reservations that are not utilized due to a latency reselection, a size reselection or an unutilized reservation are referred to as *wasted reservations*.

Size reselections, latency reselections and unutilized reservations are particularly present when vehicles generate aperiodic traffic of variable size that is characteristic of eV2X or connected automated driving applications following 3GPP [4] and ETSI standards [16]. These three MAC events generate more transmissions in selected (i.e. not reserved) resources. This increases the probability of packet collisions, which negatively impacts the performance of NR V2X mode 2 communications [11]. This is the case because it is not possible to detect a potential collision when a vehicle transmits on selected resources since the reservation of these resources has not yet been announced.

## III. Re-Evaluation in NR V2X mode 2

### A. Re-evaluation mechanism

NR V2X mode 2 introduces the re-evaluation mechanism to detect and avoid possible packet or TB collisions. With re-evaluation, vehicles verify before transmitting a TB whether the selected resources remain available or not. To do so, the vehicle must again execute step 1 of the resource selection algorithm $T_3$ slots before the transmission of a TB. $T_3$ is the maximum processing time (in slots) allowed for a vehicle to select new resources. This new execution of step 1 is referred to as *re-evaluation check* in 3GPP standards [10]. It is important to note that the re-evaluation mechanism can only be applied over selected (and not reserved) resources.

Fig. 2 illustrates the operation of the re-evaluation mechanism. The figure depicts a scenario in which a vehicle originally selects a resource located at slot $m$, and performs the re-evaluation check at slot $m$-$T_3$. The vehicle must then define a new selection window SW' within the range of slots [$m$-$T_3$+$T_1$, $m$-$T_3$+$T_2$']. The vehicle configures $T_2$' within $T_{2min} \leq T_2' \leq$PDB-($m$-$T_3$-$n$), and this study considers the case in which $T_2$' is set so that the last slot of SW ($n$+$T_2$) and SW' ($m$-$T_3$+$T_2$') coincide. The vehicle checks which resources are currently available by executing step 1 over SW' at slot $m$-$T_3$.

The 3GPP standard specifies that a vehicle performs a *re-evaluation detection* if the originally selected resource at slot $m$ is not available anymore (i.e. another vehicle has reserved it) when the vehicle executes step 1 at slot $m$-$T_3$ [13]. In this case, the re-evaluation detection triggers the execution of step 2 for selecting new resources (at $m'$ in Fig. 2) among the ones available in SW'. 3GPP refers to this new execution of step 2 as *resource replacement* [10].

We should note that a vehicle that has selected $N$>1 resources for the transmission (and retransmissions) of a TB, conducts the re-evaluation check prior to the initial transmission (at $m_1$) of the TB, i.e. at $m_1$-$T_3$. At this time, it verifies the availability of all $N$ selected resources. This is the case because all $N$ resources are eligible for a re-evaluation check before the initial transmission of the TB since they are still selected (and not reserved) resources. This is not the case as soon as resources are reserved for the retransmissions of the TB. If the re-evaluation check identifies a re-evaluation detection for all $N$ resources, the resource replacement selects the first new resource among all available resources within SW'. For the other new resources, the resource replacement must consider that the SCI can only reserve resources for retransmissions that take place up to 31 slots later than the SCI [13]. If the number of re-evaluation detections affects a number $M$ of resources smaller than $N$, the resource replacement must again select new resources considering the SCI limitations. In this case, the new resources must be in a window of +/- 31 slots around the selected resources that have not experienced a re-evaluation detection.

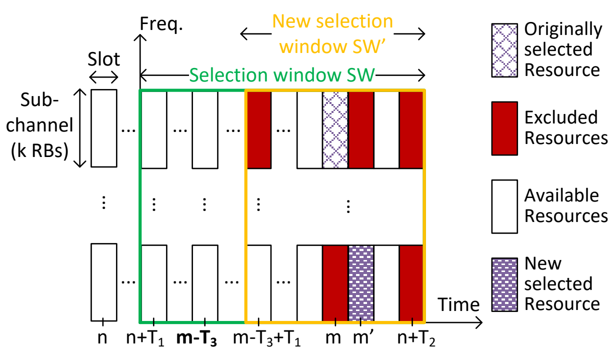



Fig. 2. NR V2X channelization and illustration of the re-evaluation mechanism in NR V2X mode 2.

The 3GPP standard specifies that the re-evaluation check process over selected resources is mandatory when a vehicle has selected new resources for the transmission of a TB [10]. A re-evaluation check is also possible when a vehicle experiences an unutilized reservation but is left to UE implementation by the 3GPP standard. In this study, we also consider these re-evaluation checks since unutilized reservations can produce packet collisions as reported in [11].

### B. *Undetectable collisions*

The re-evaluation mechanism can only detect a subset of packet collisions. When a vehicle $V_1$ executes step 1 of the resource selection algorithm $T_3$ slots before the transmission of a TB, it can avoid a collision if it detects that another vehicle $V_2$ has reserved the same resources it selected. On the other hand, $V_1$ cannot detect a potential collision with $V_2$ on the same selected resources if $V_2$ did not announce previously their reservation. This can occur because $V_2$ is transmitting the first TB after a new reselection or because of a previous unutilized reservation. In the latter case, $V_2$ could not announce in the unutilized resources that it was reserving the resources where a collision could take place with $V_1$. We should note that a new reselection of resources can occur when $RC$ is depleted and after a size or latency reselection. Overall, unutilized reservations, latency reselections, and size reselections increase the number of transmissions in selected (not reserved) resources, which increases the probability of undetectable collisions by re-evaluation.

### C. *Effective and ineffective re-evaluations*

Unutilized reservations, size reselections and latency reselections reduce the effectiveness of re-evaluation. Let's suppose that $V_2$ has transmitted an SCI with a TB at $t_1$ to announce the reservation of a resource at $t_2$ for the transmission of a new TB, but this new TB generates a size or latency reselection. In this case, $V_2$ wastes its initially reserved resource at $t_2$ and selects a new resource at $t_3$ for the transmission of the new TB. In parallel, let's suppose that $V_1$ had selected the same resource reserved by $V_2$ at $t_2$. $V_1$ executes a re-evaluation check before the transmission of its TB at $t_2$ and detects the possible collision with $V_2$. $V_1$ executes then the resource replacement to avoid the detected collision at $t_2$. However, this collision was not actually going to occur since $V_2$ does not finally transmit at $t_2$ due to the size or latency reselection generated by the new TB. In addition, the resource replacement executed by $V_1$ increases the risk of an undetectable collision since $V_1$ is now selecting a new resource. We refer to this event as an ineffective re-evaluation. An ineffective re-evaluation also occurs if $V_2$ wastes its initially reserved resource due to an unutilized reservation, and $V_1$ executes a resource replacement because it detected a possible collision with the initially reserved resource by $V_2$ that would actually not happened since $V_2$ finally wasted its reserved resource. This ineffective re-evaluation again increases the probability of packet collisions since $V_1$ has to select new resources following a resource replacement.

We should note that ineffective re-evaluations do not affect resources reserved for retransmissions of a TB. This is the case because a vehicle always utilizes a reservation for a retransmission since it is adapted in size and latency to the TB, and there is no risk of size or latency reselection. In this case, a resource replacement triggered by a reservation for a retransmission will always avoid the detected collision.

Ineffective re-evaluations can also negatively impact the latency experienced since a resource replacement increases the probability to transmit a TB at a later slot. This is the case because the selection window SW' used to select a new resource after a resource replacement starts later than the original selection window SW. The potential negative impact of ineffective re-evaluations on latency increases if all transmissions of a TB undergo a resource replacement. In this case, the resource for the first transmission following a resource replacement can be located at any slot of the SW', and all the following new resources for the retransmissions of a TB must be after the resource for the first transmission considering the SCI limitations. If only a subset of transmissions of a TB are affected by a resource replacement, the selection of these resources is limited to 31 slots after the resources that did not experience a re-evaluation detection, which reduces the risk of increasing the latency. The potential negative impact of ineffective re-evaluations on latency also depends on which transmissions are affected by the resource replacement. Let's suppose that a vehicle originally selects two resources for the initial transmission and the retransmission of a TB (*N*=2). We consider that the resources for the initial transmission are located at slot $m_1$. The vehicle executes a re-evaluation check at $m_1$-$T_3$, and SW' is defined by the range of slots [$m_1$-$T_3$+$T_1$, $m_1$-$T_3$+$T_2$']. The resource replacement can decrease the transmission latency if the new resource is selected in the range [$m_1$-$T_3$+$T_1$, $m_1$-1]. However, this is highly unlikely since the length of this range is, for example, only 3 slots if we consider $T_3$=5 slots and $T_1$=2 slots with SCS=30 kHz. The probability to decrease the latency is higher for a resource replacement over a retransmission of the TB. Let's suppose that this retransmission was originally planned at slot $m_2$ ($m_2$>$m_1$). SW' is also defined by the range of slots [$m_1$-$T_3$+$T_1$, $m_1$-$T_3$+$T_2$'] in this case, and the latency is reduced if the new resource is selected in the range [$m_1$-$T_3$+$T_1$, $m_2$-1]. This range has $m_2$-$m_1$ more slots than the range over which the initial transmission of a TB can reduce the latency following a resource replacement (i.e. [$m_1$-$T_3$+$T_1$, $m_1$-1]).

## IV. Effectiveness of Re-Evaluation

The effectiveness of re-evaluation depends on the probability of wasting a reservation for transmitting a new TB. If this probability is higher than 0.5, there will be more ineffective re-evaluations than effective ones, and resource replacements following a re-evaluation detection are more likely to degrade the reliability than improve it since the selection of new resources increases the probability of packet collisions. The impact of ineffective re-evaluations on the reliability depends on the vehicle density and channel load. This is the case because the higher the load, the higher the risk that the re-evaluation mechanism encounters an undetectable packet collision after selecting new resources following an ineffective re-evaluation. The impact of the load is present also in scenarios with less ineffective re-evaluations than effective ones, i.e. in scenarios with a probability of wasting a reservation for a new TB lower than 0.5. To understand whether re-evaluation can be effective in avoiding packet collisions, it is necessary to quantify the probability of wasting a reservation for a new TB ($P_{WR}$). This section analytically quantifies $P_{WR}$. We first calculate it when vehicles do one transmission per TB and then extend it to the case of retransmissions, particularly to the case of two transmissions per TB. We should note that two transmissions per TB is the configuration recommended by SAE [17], and is also the mode 2 configuration used in our evaluation. $P_{WR}$ is quantified considering the scenario where vehicles generate the TBs aperiodically since this is the scenario where re-evaluation is more necessary due to the higher packet collisions [11]. Following the 3GPP aperiodic traffic model [4], we consider that vehicles generate TBs with an inter-packet arrival time $\tau = \bar{x} + x(\bar{x})$, where $\bar{x}$ is a constant minimum inter-packet arrival time and $x$ is an exponential random variable of mean equal to $\bar{x}$. Table I lists the variables used to quantify $P_{WR}$.

TABLE I
VARIABLES

| Variable | Description |
|---|---|
| $P_{WR}$ | Probability of wasting a reservation for a new TB* |
| $P_{LRR}$ | Probability of a latency reselection* |
| $P_{SR}$ | Probability of a size reselection without a simultaneous latency reselection* |
| $P_{URR}$ | Probability of an unutilized reservation because the TB is generated after the reserved resources* |
| $n$ | Slot where the vehicle generates a TB |
| $m$ | Slot used to transmit the TB generated at slot $n$ ($m > n$) for one transmission per TB |
| $s_m$ | Slot where the new selected resource is located with respect to the slot $n$ for one transmission per TB |
| $T_2$ | It defines the last slot of the selection window |
| $T_1$ | Processing time (in slots) needed to select new resources |
| $\overline{s_m}$ | Slot where the slot $s_m$ is located on average |
| $\overline{s_r}$ | Slot where the resource reserved for a new TB is located on average for one transmission per TB |
| $n_2$ | Slot where a new TB is generated after the slot $n$ |
| $\overline{s_s}$ | Slot where the selected resource available after an unutilized reservation is located on average |
| $\tau$ | Inter-packet arrival time |
| $x$ | Exponential random variable of mean equal to $\bar{x}$ ms |
| $P_{LRR1}$ | Probability that the vehicle reserves a resource that does not fulfill the PDB of the new TB* |
| $P_{LRR2}$ | Probability that the vehicle generates a TB after the reserved resource and the following selected resource does not fulfill the PDB of the new TB* |
| $P_{SRR}$ | Probability of a size reselection with possible simultaneous latency reselections* |
| $P_{SRR}(i)$ | Probability of size reselection when the vehicle is using $i$ sub-channels |
| $P_{RES}(i)$ | Probability that the vehicle uses a resource of $i$ sub-channels |
| $P_G(i)$ | Probability that the vehicle generates a TB that needs $i$ sub-channels |
| $P_{LRR}(i)$ | Probability of using a resource of $i$ sub-channels after a latency reselection |
| $P_{SR}(i)$ | Probability of using a resource of $i$ sub-channels after a size reselection without a simultaneous latency reselection |
| $P_{RC>0}(i)$ | Probability of using the same resource of $i$ sub-channels when the *RC* is higher than 0 |
| $P_{RC=0}(i)$ | Probability of using a resource of $i$ sub-channels when the *RC* is equal to 0 |
| $P_{GNL}(i)$ | Probability of generating a TB that needs $i$ sub-channels to be transmitted and does not produce a latency reselection |
| $\overline{P_{RC}}(i)$ | Average of the probabilities of using the same resource of $i$ sub-channels to transmit from 1 to *RC*-1 consecutive TBs |
| $P_{RC}(i,k)$ | Probability of using the same resource of $i$ sub-channels to transmit $k$ consecutive TBs |
| $P_k$ | Probability to keep the same resources |
| $P_{RCN}(i)$ | Probability of using a new resource of $i$ sub-channels when the *RC* is equal to 0 |
| $P_{RCK}(i)$ | Probability of keeping the same resource of $i$ sub-channels when the *RC* is equal to 0 |
| $P_{kp}(i)$ | Probability of using the same resource of $i$ sub-channels during *RC* consecutive TBs |
| $\overline{P_{kp}}$ | Probability of using the same resource of any number of sub-channels during *RC* consecutive TBs |
| $P_{URS}$ | Probability of generating a TB after the reserved resource that does not produce a latency reselection |
| $m_1$ | Slot where the new selected resource for the initial transmission is located for two transmissions per TB |
| $m_2$ | Slot where the new selected resource for the retransmission is located |
| $\overline{s_{m1}}$ | Slot where the new selected resource for the initial transmission is located on average for two transmissions per TB |

TABLE I
(CONTINUED.) VARIABLES

| Variable | Description |
|---|---|
| $\overline{s_{m2}}$ | Slot where the new selected resource for the retransmission is located on average |
| $\bar{\Delta}_{m1m2}$ | Average gap in number of slots between $m_1$ and $m_2$ |
| $\overline{s_{r1}}$ | Slot where the resource reserved for the initial transmission of a new TB is located on average for two transmissions per TB |
| $\overline{s_{r2}}$ | Slot where the resource reserved for the retransmission of a new TB is located on average |
| $\overline{s_{s2}}$ | Slot where the selected resource for the retransmission of the TB is located on average after the vehicle does not utilize the reserved resources |
| * This variable is also defined for two transmissions per TB with the same description, including an R as a superscript in the variable name | |

## A. One transmission per TB

A reservation to transmit a new TB is wasted when there is a latency reselection, a size reselection or an unutilized reservation because the vehicle has generated the new TB after the reserved resource. We can then define the probability of wasting a reservation as:

$$P_{WR} = P\,(LRR \cup SR \cup URR) \tag{1}$$

where *P(y)* is the probability of *y*, *LRR* is a latency reselection, *SR* is a size reselection without a simultaneous latency reselection, and *URR* is an unutilized reservation. A TB can simultaneously generate a size and latency reselection. *SR* does not include possible size reselections with simultaneous latency reselections since these are already included in *LRR*. *URR* does not include possible wasted reservations caused by a latency or size reselection triggered by the TB that is generated after the reserved resource since these are already included in *LRR* and *SR*. *LRR*, *SR* and *URR* are then exclusive events because they cannot occur simultaneously, and $P_{WR}$ can be expressed as [18]:

$$P_{WR} = P_{LRR} + P_{SR} + P_{URR} \tag{2}$$

where $P_{LRR}$, $P_{SR}$ and $P_{URR}$ are the probabilities of *LRR*, *SR* and *URR* respectively. To compute these probabilities, we define *n* as the slot where the vehicle generates a TB. This TB is transmitted at the new selected resource located at slot *m*. We define $s_m$ as the slot where the new selected resource is located with respect to the slot *n* and $\overline{s_m}$ as the slot where $s_m$ is located on average. $\overline{s_m}$ depends on the length of the selection window (and hence on $T_2$ and $T_1$) and can be computed as:

$$\overline{s_m} = \overline{m-n} = \frac{\sum_{i=T_1}^{T_2} i}{T_2 - T_1 + 1} \tag{3}$$

We define $\overline{s_r}$ as the slot where the resource reserved for a new TB is located on average, and $n_2$ as the slot where a new TB is generated. $\overline{s_r}$ is equal to the sum of $\overline{s_m}$ and the *RRI* (expressed in number of slots). We define $\overline{s_s}$ as the slot where the selected resource available after an unutilized reservation is located on average. $\overline{s_s}$ is equal to the sum of $\overline{s_m}$ and *2*RRI*. $n_2$-*n* is the inter-packet arrival time $\tau$ (in number of slots):

$$n_2 - n = \tau = \left(\bar{x} + x(\bar{x})\right) * 2^{\mu} \tag{4}$$

where *x* is an exponential random variable of mean $\bar{x}$ ms and μ represents the numerology configured[2].

$P_{LRR}$ is the sum of the probability $P_{LRR1}$ that the vehicle reserves a resource that does not fulfill the PDB (Packet Delay Budget) of the new TB, plus the probability $P_{LRR2}$ that the vehicle generates a TB after the reserved resource and the following selected resource (located *RRI* slots after) does not fulfill the PDB of the new TB. $P_{LRR1}$ can be expressed as:

$$P_{LRR1} = P\left((\tau + PDB) < \overline{s_r}\right) = cdf_{\tau}\,(\overline{s_r} - PDB) \tag{5}$$

where $cdf_{\tau}(y)$ is the cumulative distribution function of $\tau$ evaluated at *y*. $P_{LRR2}$ can be expressed as:

$$\begin{aligned} P_{LRR2} &= P\,((\tau > \overline{s_r}) \cap ((\tau + PDB) < \overline{s_s})) \\ &= cdf_{\tau}\,(\overline{s_s} - PDB) - cdf_{\tau}\,(\overline{s_r}) \end{aligned} \tag{6}$$

$P_{SR}$ represents the probability of a size reselection without simultaneous latency reselections. It can be estimated as:

$$P_{SR} = P_{SRR} * (1 - P_{LRR}) \tag{7}$$

where $P_{SRR}$ is the probability of a size reselection with possible simultaneous latency reselections. Eq. (7) shows that $P_{SR}$ depends on $P_{LRR}$. This means that the events *SR* and *LRR* are dependent. Since *SR* and *LRR* are exclusive events, *SR* depends on the non-occurrence of *LRR* [18]. This is modeled in eq. (7) with the multiplication of $(1 - P_{LRR})$. $P_{SRR}$ can be computed as:

$$P_{SRR} = \sum_{i=\min(i)}^{\max(i)} P_{SRR}(i) \tag{8}$$

where $P_{SRR}(i)$ is the probability of size reselection when the vehicle is using *i* sub-channels. A size reselection happens when the vehicle generates a TB that needs *j* sub-channels to be transmitted and *j*>*i*. $P_{SRR}(i)$ can then be computed as the multiplication of the probability that the vehicle uses a resource of *i* sub-channels ($P_{RES}(i)$) and the probability that it generates a TB that needs *j*>*i* sub-channels ($P_G(j > i)$).

$$P_{SRR}(i) = P_{RES}(i) * P_G(j > i) \tag{9}$$

$P_{RES}(i)$ can be computed as the sum of the following probabilities:

$$\begin{aligned} P_{RES}(i) = P_{LRR}(i) + P_{RC>0}(i) + P_{RC=0}(i) \\ + P_{SR}(i) \end{aligned} \tag{10}$$

where $P_{LRR}(i)$ is the probability of using a resource of *i* sub-channels after a latency reselection, $P_{SR}(i)$ is the probability of using a resource of *i* sub-channels after a size reselection without a simultaneous latency reselection, $P_{RC>0}(i)$ is the probability of using the same resource of *i* sub-channels when the *RC* is higher than 0, and $P_{RC=0}(i)$ is the probability of using a resource of *i* sub-channels when the *RC* is equal to 0. $P_{LRR}(i)$ is computed as a function of the probability of latency reselection ($P_{LRR}$) and the probability of generating a TB that needs *i* sub-channels ($P_G(i)$):

$$P_{LRR}(i) = P_{LRR} * P_G(i) \tag{11}$$

The probability $P_{RC>0}(i)$ is estimated as:

$$P_{RC>0}(i) = \overline{P_{RC}}(i) * P_{GNL}(j \le i) \tag{12}$$

[2] In the case of periodic traffic, $\tau$ should be set equal to the traffic periodicity multiplied by $2^{\mu}$, where μ is the numerology.

where $P_{GNL}(j \leq i)$ is the probability of generating a TB that needs $j \leq i$ sub-channels to be transmitted and does not produce a latency reselection. It can be expressed as:

$$P_{GNL}(j \leq i) = (1 - P_{LRR}) * \sum_{j=\min(i)}^{i} P_G(j) \tag{13}$$

$\overline{P_{RC}}(i)$ is the average of the probabilities of using the same resource of *i* sub-channels to transmit from 1 to *RC*-1 consecutive TBs. It is computed as:

$$\overline{P_{RC}}(\mathrm{i}) = P_G(i) * \frac{\sum_{k=1}^{\overline{RC}-2} P_{RC}(i,k)}{\overline{RC} - 2} \tag{14}$$

where $\overline{RC}$ is the average value of the *RC* and $P_{RC}(i,k)$ is the probability of using the same resource of *i* sub-channels to transmit *k* consecutive TBs. Eq. (14) limits the number of consecutive TBs to $\overline{RC}$-2 TBs so that the *RC* is always higher than 0. A vehicle uses the same resource of *i* sub-channels for *k* consecutive TBs if the TBs fit in the same resource of *i* sub-channels and the *k* TBs do not trigger any latency reselection. $P_{RC}(i,k)$ can then be expressed as:

$$P_{RC}(i,k) = (P_{GNL}(j \leq i))^k \tag{15}$$

When the *RC* is equal to 0, a vehicle selects a new resource with probability (1-$P_k$). $P_{RC=0}(i)$ is equal to:

$$P_{RC=0}(i) = P_{RCN}(i) + P_{RCK}(i) \tag{16}$$

where $P_{RCN}(i)$ and $P_{RCK}(i)$ are the probabilities of using a new resource of *i* sub-channels or keeping the same resource of *i* sub-channels when the *RC* is equal to 0. $P_{RCK}(i)$ is computed as:

$$P_{RCK}(i) = P_{kp}(i) * P_k * P_{GNL}(j \leq i) \tag{17}$$

where $P_{kp}(i)$ is the probability of using the same resource of *i* sub-channels during *RC* consecutive TBs. This can happen when the new selected resource needs *i* sub-channels to transmit the first TB, and the same resource is used for the following *RC*–1 TBs. $P_{kp}(i)$ is then equal to:

$$P_{kp}(i) = P_G(i) * P_{RC}(i, \overline{RC} - 1) \tag{18}$$

A vehicle selects a new resource of *i* sub-channels after *RC* is depleted if the first TB needs *i* sub-channels to be transmitted. The probability $P_{RCN}(i)$ of using a new resource of *i* sub-channels can be computed as:

$$P_{RCN}(i) = \overline{P_{kp}} * (1 - P_k) * P_G(i) \tag{19}$$

where $\overline{P_{kp}}$ is the probability of using the same resource of any number of sub-channels during *RC* consecutive TBs. $\overline{P_{kp}}$ is estimated as:

$$\overline{P_{kp}} = \sum_{j=\min(i)}^{\max(i)} P_G(j) * P_{kp}(j) \tag{20}$$

For brevity, we define the variable $P_X(i)$ as:

$$P_X(i) = P_{LRR}(i) + P_{RC>0}(i) + P_{RC=0}(i) \tag{21}$$

To compute $P_{RES}(i)$, we finally need to derive the probability $P_{SR}(i)$ that a vehicle uses *i* sub-channels after a size reselection without a simultaneous latency reselection:

$$P_{SR}(i) = P_{SR} * P_G(i) \tag{22}$$

Using eq. (7), we can express $P_{SR}(i)$ as:

$$P_{SR}(i) = P_{SRR} * (1 - P_{LRR}) * P_G(i) \tag{23}$$

Using eqs. (8), (9), (10), (21), (23) we can express $P_{SRR}$ as:

$$P_{SRR} = \sum_{\mathrm{i}=\min(i)}^{\max(i)} (P_G(j > i) * (P_X(i) + P_{SRR} * (1 - P_{LRR}) * P_G(i))) \tag{24}$$

We can then derive $P_{SRR}$ as:

$$P_{SRR} = \frac{\sum_{\mathrm{i}=\min(i)}^{\max(i)} (P_G(j > i) * P_X(i))}{1 - (1 - P_{LRR}) * \sum_{\mathrm{i}=\min(i)}^{\max(i)} (P_G(j > i) * P_G(i))} \tag{25}$$

Using $P_{SRR}$ and $P_{LRR}$, we can derive $P_{SR}(i)$ using eq. (23) and $P_{SR}$ using eq. (7). $P_{SR}$ can then be finally expressed as:

$$P_{SR} = \frac{(1 - P_{LRR}) * \sum_{\mathrm{i}=\min(i)}^{\max(i)} (P_G(j > i) * P_X(i))}{1 - (1 - P_{LRR}) * \sum_{\mathrm{i}=\min(i)}^{\max(i)} (P_G(j > i) * P_G(i))} \tag{26}$$

To compute $P_{WR}$, we finally need to derive $P_{URR}$ that represents the probability of an unutilized reservation because the TB is generated after the reserved resource. $P_{URR}$ does not account for the cases where the TB generated after the reserved resource triggers a latency reselection or a size reselection. It can then be expressed as:

$$P_{URR} = P_{URS} * (1 - P_{SR}) \tag{27}$$

where $P_{URS}$ is the probability of generating a TB after the reserved resource that does not produce a latency reselection and $(1 - P_{SR})$ represents the probability that a TB does not produce a size reselection. $P_{URS}$ is defined as:

$$P_{URS} = P\left((\tau > \overline{s_r}) \cap ((\tau + PDB) > \overline{s_s})\right) = 1 - cdf_\tau\left(\max(\overline{s_r}, \overline{s_s} - PDB)\right) \tag{28}$$

### *B. Two transmissions per TB*

In the case that a vehicle does two transmissions per TB (the initial transmission and a retransmission), the resources reserved for a new TB are also wasted if there is a latency reselection, a size reselection or an unutilized reservation because the TB is generated after the reserved resources. Compared to the scenario with one transmission per TB, the retransmission of a TB modifies when these three events happen and therefore their probabilities that we denote now $P_{LRR}^R$, $P_{SR}^R$ and $P_{URR}^R$. The probability $P_{WR}^R$ of wasting a reservation when a vehicle does two transmissions per TB is the sum of $P_{LRR}^R$, $P_{SR}^R$ and $P_{URR}^R$.

The process followed to compute $P_{WR}^R$ is similar to the one followed when each TB is transmitted only once. We define $m_1$ and $m_2$ as the slots where the new selected resources for the initial transmission and the retransmission are located respectively. We define $\overline{s_{m1}}$ and $\overline{s_{m2}}$ as the slots where the new selected resources for the initial transmission and retransmission are located on average, respectively, with respect to the slot *n* where a vehicle generates a new TB and selects new resources. The first selected resource is chosen randomly (Section II) like for the scenario where each TB is transmitted only once; it is hence equal on average to $\overline{s_m}$ (eq. (3), Section IV.A). Let's suppose that this first selected resource is located at slot $m_\alpha$. The second selected resource must be located within the window [$m_\alpha$-31, $m_\alpha$+31]. We can then estimate $\overline{s_{m1}}$ and $\overline{s_{m2}}$ as:

$$\overline{s_{m1}} = \overline{m_1 - n} = \overline{s_m} - \frac{\bar{\Delta}_{m1m2}}{2} \quad (29)$$

$$\overline{s_{m2}} = \overline{m_2 - n} = \overline{s_m} + \frac{\bar{\Delta}_{m1m2}}{2} \quad (30)$$

where $\bar{\Delta}_{m1m2}$ is the average gap in number of slots between $m_1$ and $m_2$. It is computed as:

$$\bar{\Delta}_{m1m2} = \frac{\max(\Delta_{m1m2}) + \min(\Delta_{m1m2})}{2} \quad (31)$$

where $\max(\Delta_{m1m2})$ and $\min(\Delta_{m1m2})$ are the maximum and minimum gap between $m_1$ and $m_2$. The minimum gap is 1 slot because the initial transmission and the retransmission must be located in different slots. The maximum gap is 31 slots so that both transmissions are within a window of 32 slots (Section II).

$P^R_{LRR}$ can also be defined as the sum of the probability $P^R_{LRR1}$ that the vehicle reserves a resource that does not fulfill the PDB of the new TB, plus the probability $P^R_{LRR2}$ that the vehicle generates a TB after the reserved resource and the following selected resource does not fulfill the PDB of the new TB. We define $\overline{s_{r1}}$ and $\overline{s_{r2}}$ as the slots where the resources reserved for the initial transmission and retransmission of a new TB are located on average, respectively. $\overline{s_{s2}}$ is the slot where the selected resource for the retransmission of the TB is located on average after the vehicle does not utilize the reserved resources. These resources are not utilized in the case of a latency reselection, and can be computed as:

$$\overline{s_{r1}} = \overline{s_{m1}} + RRI \quad (32)$$

$$\overline{s_{r2}} = \overline{s_{m2}} + RRI \quad (33)$$

$$\overline{s_{s2}} = \overline{s_{m2}} + 2 * RRI \quad (34)$$

To compute $P^R_{LRR1}$ and $P^R_{LRR2}$, we should take into account that if the resource for the retransmission of the TB does not fulfill the PDB of the new TB, then the vehicle reselects the resources for the initial transmission and the retransmission [10]. $P^R_{LRR1}$ can then be calculated as $P_{LRR1}$ (eq. (5)) but replacing $\overline{s_r}$ by $\overline{s_{r2}}$. To compute $P^R_{LRR2}$, we should also note that if the vehicle generates the TB after the resource reserved for the initial transmission, then the vehicle uses the next selected resources available for the initial transmission and the retransmission [10] even if the resource reserved for the retransmission is located after generation of the TB. $P^R_{LRR2}$ can then be calculated as $P_{LRR2}$ (eq. (6)) but replacing $\overline{s_r}$ by $\overline{s_{r1}}$ and $\overline{s_s}$ by $\overline{s_{s2}}$.

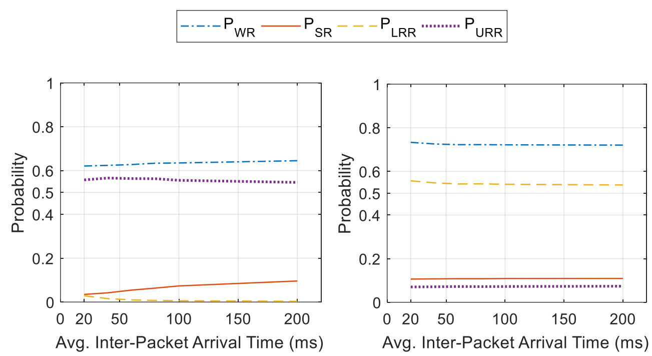
The probability $P^R_{SR}$ of size reselection without a simultaneous latency reselection is estimated as:

$$P^R_{SR} = P^R_{SRR} * (1 - P^R_{LRR}) \quad (35)$$

$P^R_{SRR}$ is computed as $P_{SRR}$ (Section IV.A) but replacing $P_{LRR}$ by $P^R_{LRR}$ in eqs. (11) and (13). Similarly, $P^R_{URR}$ is calculated as $P_{URR}$ (Section IV.A) but replacing $P_{SR}$ by $P^R_{SR}$ in eq. (27), as well as $\overline{s_r}$ by $\overline{s_{r1}}$ and $\overline{s_s}$ by $\overline{s_{s2}}$ in eq. (28).

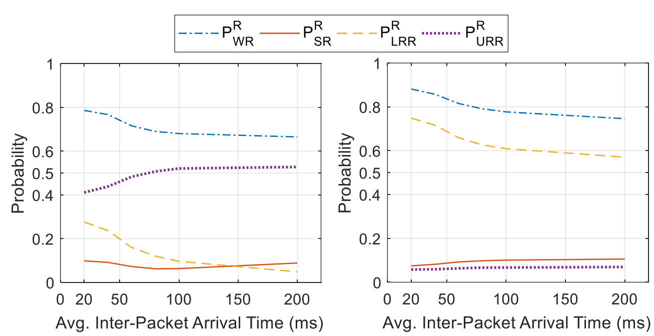
### *C. Numerical evaluation*

The effectiveness of re-evaluation depends on the probability of wasting a reservation for a new TB. Fig. 3 and Fig. 4 plot this probability with respect to the average inter-packet arrival time (following the 3GPP guidelines [4]) for one and two transmissions per TB, respectively, when vehicles generate aperiodic traffic of variable size. Vehicles generate TBs with an inter-packet arrival time $\tau = \bar{x} + x(\bar{x})$, where $\bar{x}$ is a constant minimum inter-packet arrival time and $x$ is an exponential random variable of mean equal to $\bar{x}$. $\bar{x}$ is equal to the average inter-packet arrival time divided by 2. NR V2X mode 2 is set to operate over 20 MHz in the 5.9 GHz band using a subcarrier spacing of 30 kHz (i.e. the numerology µ is equal to 1). The sub-channel size is set to 12 RBs, and there are 4 sub-channels per slot. The size of TBs is uniformly distributed in the [200, 1200] bytes range (with a 200-byte step). Vehicles use the MCS (Modulation and Coding Scheme) index 13 (16QAM modulation and coding rate equal to 0.5) to transmit each TB. In this case, TBs of 200, 400, 600, 800, 1000 and 1200 bytes require 1, 2, 3, 3, 4 and 4 sub-channels, respectively, to be transmitted along with their associated SCI. $T_1$ and $T_2$ define the bounds of the selection window. $T_1$ is set equal to 2 slots, and $T_2$ is set equal to the PDB. The probability $P_k$ to keep the same resources has been set to 0. Fig. 3 and Fig. 4 also plot the probabilities of latency reselection (*LRR*), size reselection (*SR*) and unutilized reservation because the vehicle has generated the TB after the reserved resource (*URR*).The results are derived for two strategies for the selection of the *RRI* [11]: average *RRI* (*RRI* is set equal to the average inter-packet arrival time) and minimum *RRI* (*RRI* is set equal to the minimum of the inter-packet arrival time). The PDB is set equal to the minimum inter-packet arrival time following the 3GPP guidelines [4].




a) Minimum *RRI* b) Average *RRI*

Fig. 3. Probability of wasting a reservation for a new TB ($P_{WR}$) for one transmission per TB.




a) Minimum *RRI* b) Average *RRI*

Fig. 4. Probability of wasting a reservation for a new TB ($P^R_{WR}$) for two transmissions per TB.

The figures show that the probability of wasting a reservation for a new TB is higher than 0.5 in all evaluated scenarios when considering aperiodic traffic of variable size. In this case, a resource replacement triggered by re-evaluation is more likely to degrade the reliability than improve it because the detected collision might not happen and selecting new resources increases the probability of packet collision (Section III). In line with the trends reported in [11], the figures show that the minimum *RRI* strategy reduces the probability of latency reselections at the cost of increasing the probability of unutilized reservations. On the other hand, the average *RRI* strategy reduces the probability of unutilized reservations but increases the probability of latency reselections. The probability of size reselection (without simultaneous latency reselections) is low in all scenarios.

Fig. 3 shows that the probability of wasting a reservation for a new TB is maintained constant with respect to the average inter-packet arrival time for one transmission per TB. The variations in the generation of the traffic and PDB are compensated with the adaptation of the *RRI* to the inter-packet arrival time. This trend is not observed for two transmissions per TB (Fig. 4) because the probability of latency reselections is higher than when there is one transmission per TB. This increase cannot be fully compensated with the adaptation of the *RRI* to the inter-packet arrival time, and the impact is higher with more stringent latency requirements, i.e. with low PDBs (corresponding to low inter-packet arrival times).

## V. Selective Re-Evaluation Mechanism

The previous section has demonstrated that the standard re-evaluation mechanism can produce more ineffective re-evaluations than effective ones when vehicles generate aperiodic traffic of variable size. In fact, the previous section has showed that, for all the evaluated scenarios, a resource replacement triggered by the standard re-evaluation mechanism is more likely to degrade the reliability than improve it (i.e. $P_{WR} > 0.5$). To address this challenge, we propose a simple, yet effective, selective re-evaluation mechanism that modifies the standard re-evaluation mechanism to avoid ineffective re-evaluations.

The proposal only executes a resource replacement following a re-evaluation detection if the resource replacement is estimated to be effective, i.e. it is certain it will avoid a collision. Effective resource replacements are those generated by a re-evaluation detection triggered by a reservation for a retransmission of a TB. This is the case because a vehicle always utilizes a reservation for a retransmission since it is adapted in size and latency to the TB, and there is no risk of size or latency reselection. In this case, a resource replacement triggered by a reservation for a retransmission will always avoid a detected collision. Our proposal is therefore applicable only when NR V2X mode 2 is configured with retransmissions. However, we should remind that two transmissions per TB (i.e. one initial transmission and one retransmission of the TB) is the configuration recommended by SAE [17], and also the mode 2 configuration used in this study.

On the other hand, it is not possible to guarantee that a resource replacement following a re-evaluation detection triggered by a reservation for a new TB will be effective and will for sure avoid a detected collision (Section IV.C). The resource replacement might be ineffective if the new TB generates a size or latency reselection, and the colliding vehicle ultimately wastes the reservation announced for the new TB; these circumstances are more likely with aperiodic traffic of variable size. To avoid ineffective re-evaluations, the selective re-evaluation proposal does not execute the resource replacements following re-evaluation detections triggered by a reservation for a new TB. To identify effective resource replacements, a vehicle analyzes the information received in SCIs and checks whether a reservation by another vehicle that triggers a re-evaluation detection is for a retransmission of a TB or for the transmission of a new TB [19]. The steps of the proposed selective re-evaluation mechanism are summarized in Algorithm I.

The proposed selective re-evaluation mechanism can also reduce the probability of undetectable collisions by not executing potentially ineffective resource replacements. This is the case because a resource replacement results in the selection of new resources, and it is not possible to detect collisions when vehicles are selecting new resources (no reservation has yet been announced). In addition, the vehicle that avoids the resource replacement maintains its selected resource and hence reduces the probability that other vehicles select the same resource as they can detect it is occupied. Finally, we should note that the selective re-evaluation proposal can also reduce the latency since resource replacements increase the probability of high latencies (Section III.C).

Algorithm I.
Input: initially selected resources
Output: selected resources
Execution: $T_3$ slots before the resource for the first transmission

```
Define the new selection window SW'
Execute re-evaluation check over SW'
For each initially selected resource do
    If re-evaluation detection is not triggered then
        Resource replacement not executed
        Selected resource = initially selected resource
    Else
        Check the type of reservation in the received SCI
        If triggered by a reservation for a retransmission then
            Resource replacement executed
            Selected resource = new selected resource
        Else
            Resource replacement not executed
            Selected resource = initially selected resource
        End If
    End If
End For
```

## VI. Simulation Environment

The analysis conducted in Section IV allowed us to explain and analytically quantify the effectiveness of re-evaluations generated by the standard re-evaluation mechanism. The observation that ineffective re-evaluations prevail when vehicles generate aperiodic traffic of variable size are at the origin of the selective re-evaluation proposal. A thorough evaluation and comparison of the standard and selective re-evaluation mechanisms requires the use of simulation. We use an NR V2X mode 2 simulator implemented by the authors in ns-3 following the 3GPP standards and guidelines [13][10].

NR V2X mode 2 is set to operate over 20 MHz in the 5.9 GHz band using a subcarrier spacing of 30 kHz. The sub-channel size is set to 12 RBs, and there are 4 sub-channels per slot. At the MAC layer, $T_0$ and $T_{proc,0}$ define the bounds of the sensing window, and they are configured equal to 2200 slots and 1 slot, respectively. $T_1$, $T_{2min}$ and $T_2$ define the bounds of the selection window. $T_1$ and $T_{2min}$ are set equal to 2 slots, and $T_2$ is set equal to the PDB. The RSRP threshold used in step 1 to decide if a resource is excluded or not is set to -128 dBm (i.e. its minimum value) following [20]. The threshold for the percentage of resources that vehicles must have available after executing the step 1 is set to 20% (i.e. its minimum value). We consider that vehicles select 2 resources in step 2 (i.e. $N$ is equal to 2) following the configuration recommended by SAE [17]. $T_3$ is configured equal to 5 slots following [13]. The *RRI* is selected following the minimum *RRI* strategy [11]. When *RC* is depleted, the probability $P_k$ to keep the same resources has been set to 0.

The simulator models the shadowing and pathloss using the reference 3GPP models in [4]. The shadowing is modeled using a log-normal distribution (with a mean of 0 dB and a standard deviation of 3 dB) and includes spatial shadowing correlation. The sensitivity has been set to -103.5 dBm according to [21], and the transmission power has been set to 23 dBm. Vehicles use the MCS index 13 (16QAM modulation and coding rate equal to 0.5) to transmit each TB. In this case, TBs of 190, 200, 300, 400, 600, 800, 1000 and 1200 bytes require 1, 1, 2, 2, 3, 3, 4 and 4 sub-channels, respectively, to be transmitted along with their associated SCI. We use lookup tables from 3GPP working documents to model the transmissions of the TB [22] and SCI [23] at the PHY layer. These lookup tables relate the Block Error Rate (BLER) vs Signal to Interference plus Noise Ratio (SINR).

We consider the 3GPP 5 km highway scenario with 3 lanes in each direction [4], vehicles driving at 70 km/h, and vehicle densities of 50 veh/km and 100 veh/km. Vehicles generate TBs following the 3GPP aperiodic and periodic traffic models [2]. In the aperiodic model, vehicles generate TBs with an inter-packet arrival time $\tau = \bar{x} + x(\bar{x})$, where $\bar{x}$ is a constant minimum inter-packet arrival time and $x$ is an exponential random variable of mean equal to $\bar{x}$. We evaluate low ($\bar{x} = 100$ ms), medium ($\bar{x} = 50$ ms) and high intensity ($\bar{x} = 10$ ms) scenarios, with the PDB set equal to $\bar{x}$ in all three scenarios. For all the scenarios, the size of TBs is uniformly distributed in the [200, 1200] bytes range (with a 200-byte step). We also evaluate periodic traffic of variable size following 3GPP guidelines in [4]. In this case, vehicles generate periodic TBs with a size that follows the pattern {300, 190, 190, 190, 190} bytes and a random starting point. The inter-packet arrival time for the low, medium and high intensity periodic scenarios is set equal to 200 ms, 100 ms and 20 ms, respectively. The PDB is equal to the inter-packet arrival time.

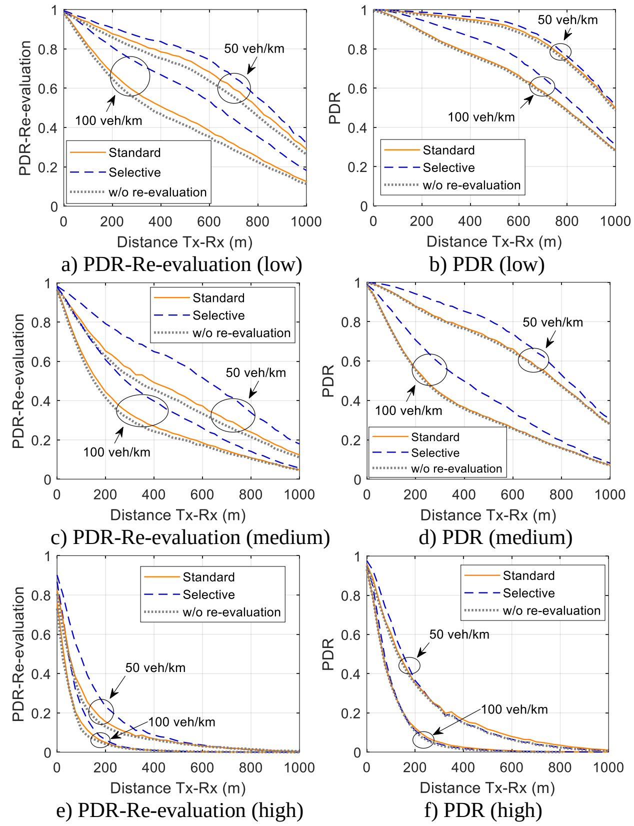



Fig. 5. Reliability of the standard and selective re-evaluation mechanisms as well as NR V2X mode 2 without re-evaluation for aperiodic traffic of variable size in low, medium and high intensity scenarios with 50 and 100 veh/km.

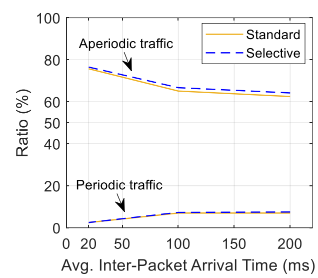



Fig. 6. Ratio of wasted reservations (*WR*, Section IV.B). This is the ratio of reservations for a new TB that are wasted to the total number of reservations for new TBs for 50 and 100 veh/km. Average inter-packet arrival times of 20, 100 and 200 ms correspond to the high, medium and low intensity scenarios respectively.

## VII. Evaluation

Fig. 5 compares the Packet Delivery Ratio (PDR) of the standard and selective re-evaluation schemes with aperiodic traffic of variable size. Fig. 5 also shows the PDR of NR V2X mode 2 without re-evaluation. We should note that a TB is successfully decoded if at least 1 out of the $N$ transmissions of a TB is successfully decoded. The comparison is done only for the transmissions that have experienced at least one re-evaluation detection (Fig. 5-left, PDR–Re-evaluation) and for all the transmissions (Fig. 5-right, PDR). Fig. 5 reports results for the low, medium and high intensity scenarios and densities of 50 and 100 veh/km. Fig. 5-left clearly shows that the selective re-evaluation mechanism improves the effectiveness of the re-evaluation process and hence the reliability under all the studied conditions. This is the case because the selective re-evaluation mechanism executes only the resource replacements that it is certain will result in a packet collision, i.e. those where the re-evaluation detection is triggered by a reservation for a retransmission. In contrast, the standard re-evaluation mechanism always executes a resource replacement after a re-evaluation detection, and Fig. 5-left shows that this does not increase the reliability due to the ineffective re-evaluations discussed in Section III.C. Fig. 5-left also shows that NR V2X mode 2 without re-evaluation does not improve the reliability despite avoiding ineffective re-evaluations. This occurs because NR V2X mode 2 without re-evaluation does not prevent packet collisions that are certain to happen, i.e. in cases where the re-evaluation detection is triggered by a reservation for a retransmission. There is a trade-off between the advantages and disadvantages of the standard re-evaluation mechanism and NR V2X mode 2 without re-evaluation, leading to similar reliability levels. The selective re-evaluation mechanism is the best scheme evaluated, as it presents the advantages of both the standard re-evaluation mechanism and NR V2X mode 2 without re-evaluation.

The selective proposal significantly reduces the ratio of executed resource replacements (ReRR) compared to the standard mechanism. Under the low intensity scenario, the standard mechanism experiences a ReRR of 40% and 52% with 50 and 100 veh/km, respectively. The selective proposal reduces these values to 17% and 25% respectively. Reduction levels above 50% are also observed under the medium and high intensity scenarios. The improvements observed in Fig. 5-left with the selective proposal are primarily due to the fact that many of the detected collisions involving reservations for a new TB would not actually occur (Section III.C) due to wasted reservations. The selective proposal avoids the resource replacements triggered by these collisions compared to the standard mechanism. In fact, Fig. 6[3] shows that the ratio of wasted reservations for new TBs is significantly higher than 50% with aperiodic traffic of variable size for both the standard and selective re-evaluation mechanisms, which explains the PDR improvements obtained with the proposed selective re-evaluation mechanism compared to the standard one.

Fig. 7 compares the Packet Collision Ratio (PCR) of the standard and selective re-evaluation schemes with aperiodic traffic of variable size. PCR is defined as the ratio of TBs that are not successfully received due to packet collisions to the total number of transmitted TBs. Fig. 7 shows that the selective re-evaluation mechanism can reduce the packet collisions experienced by the standard re-evaluation mechanism. With the selective re-evaluation proposal, a vehicle maintains the same selected resource after a re-evaluation detection is triggered by a wasted reservation (Section V). In this case, the vehicle does not select new resources and avoids the risk of packet collisions during the selection of new resources. In this case, the selective re-evaluation mechanism improves not only the reliability of transmissions that have experienced a re-evaluation detection but also the reliability of transmissions that have not experienced any re-evaluation detection. This, together with the improvements obtained for the transmissions that have experienced at least one re-evaluation detection (Fig. 5-left, PDR–Re-evaluation), explain the PDR improvements in Fig. 5-right and the reduction of PCR in Fig. 7. The PDR improvements obtained with the selective proposal (Fig. 5-right) are particularly important in the low and medium intensity scenarios as the density and channel load increases. This is the case because the higher the load, the higher the risk that the standard re-evaluation mechanism encounters an undetectable packet collision after executing a resource replacement following a detected collision that was not going to actually happen (i.e. after an ineffective re-evaluation). In fact, Fig. 7 shows that the higher the load, the higher the risk of packet collisions.

The gains obtained with the selective proposal decrease for the high intensity scenario because the scenario is so loaded that it is not possible to avoid collisions anyway as shown in Fig. 7(c). In fact, the high loads experienced in this scenario require vehicles to execute up to 13 iterations of step 1 of the resource allocation algorithm in mode 2 to increase the RSRP threshold and reach the minimum percentage of available resources in the selection window (Section II.A) with 100 veh/km. This is in contrast with only two iterations under the low intensity scenario. Increasing the RSRP threshold increases the probability of including reserved resources among the candidate resources, and therefore the probability of packet collisions (independently of the re-evaluation mechanism utilized).

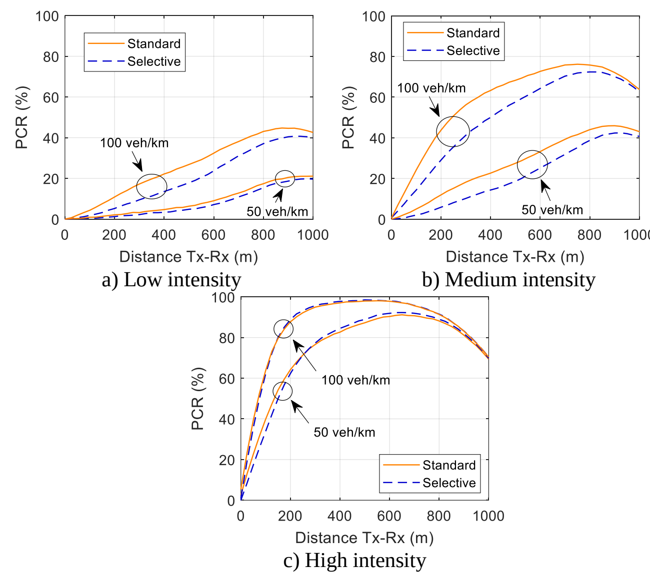
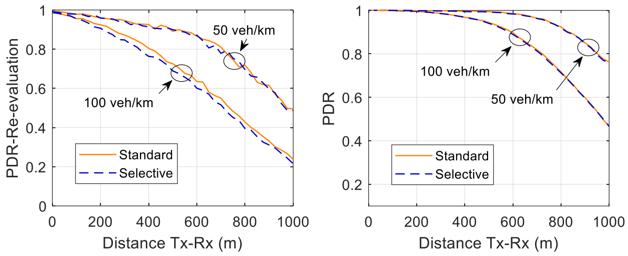



Fig. 7. Packet Collision Ratio (PCR) of the standard and selective re-evaluation mechanisms for aperiodic traffic of variable size in low, medium and high intensity scenarios with 50 and 100 veh/km.

Fig. 8 compares the PDR of the standard and selective re-evaluation schemes with periodic traffic of variable size in the medium intensity scenario with 50 and 100 veh/km. The results show that the selective proposal does not improve the PDR-Re-evaluation compared to the standard re-evaluation mechanism (Fig. 8(a)) under the presence of periodic traffic. This is because the ratio of wasted reservations (*WR*) is significantly lower than 50% with periodic traffic of variable size (Fig. 6) as this traffic can only generate size reselections. In this case, the number of effective re-evaluations with the standard mechanism will be higher than the number of ineffective re-evaluations (Section III.C), and the selective proposal is less effective for this traffic. In any case, Fig. 8(b) shows that the selective proposal ultimately does not degrade the PDR compared to the standard re-evaluation mechanism since the ratio of TBs that experience one or more re-evaluation detections is below 5% in all scenarios with periodic traffic of variable size, and most of the

[3] Fig. 6 is obtained using simulations but the results are fully aligned with those obtained using the analytical models in Section IV for all the scenarios.



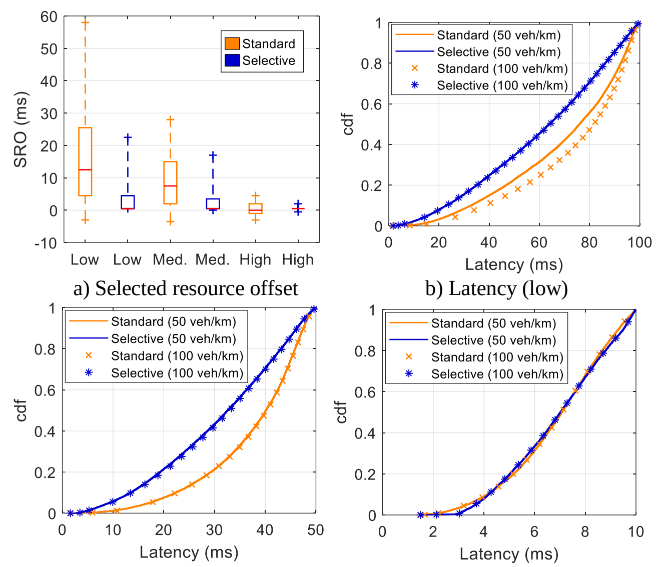

a) PDR Re-evaluation b) PDR

Fig. 8. Reliability of the standard and selective re-evaluation mechanisms for periodic traffic of variable size in the medium intensity scenario with 50 and 100 veh/km. Similar trends are observed in the other intensity scenarios.

re-evaluations are triggered by reservations for retransmissions of a TB.

The selective re-evaluation mechanism improves the reliability of 5G NR V2X transmissions by avoiding the execution of the resource replacements that may not avoid a detected collision. Reducing the number of resource replacements can improve the latency as a resource replacement requires selecting new resources, and it is more likely that this new resource is in a slot after the initially selected one (Section III.C). This is visible in Fig. 9(a) that depicts a box plot of the Selected Resource Offset (SRO) for low, medium and high intensity scenarios and 100 veh/km when vehicles generate aperiodic traffic of variable size. This metric represents the time gap between the originally scheduled transmission time and the final transmission time for those transmissions that experience at least a re-evaluation detection. The top and bottom of the box represent the 75$^{th}$ and 25$^{th}$ percentiles, respectively, while the red horizontal line represents the median. The whiskers represent the 95$^{th}$ and 5$^{th}$ percentiles. Fig. 9(a) clearly shows that the selective proposal significantly reduces the SRO since it does not execute uncertain resource replacements after a re-evaluation detection, and hence avoids the corresponding increase in SRO and latency. The higher reductions of SRO with the selective proposal are observed for the 95$^{th}$ percentile and the low intensity scenario. The highest SRO values occur when both transmissions of a TB experience a resource replacement. In this case, the new resources can be located in any slot of the selection window generated with re-evaluation, which increases the SRO[4] (Section III.C). The selective proposal reduces significantly the percentage of TBs that are affected by two resource replacements for its original transmission and its retransmission compared to the standard mechanism: 5% compared to 27% in medium and low intensity scenarios with 100 veh/km. The low intensity scenario has higher PDB values, which increases the selection window and consequently the potential delay introduced by resource replacements. As the PDB decreases, the SRO differences between re-evaluation mechanisms decrease due to the shorter selection windows. This is particularly noticeable in the high intensity scenario that has a PDB of 10 ms compared to 100 ms in the low intensity scenario.

The selective proposal significantly reduces the SRO by avoiding uncertain resource replacements, and this benefits the latency of 5G NR V2X transmissions. Fig. 9(b)-(d) depict the cumulative distribution function (cdf) of the latency of transmissions that have undergone at least one re-evaluation detection in the low, medium, and high intensity scenarios with 50 and 100 veh/km. The latency is measured from the time a vehicle generates a TB to the time it is received correctly (whether the initial transmission or the retransmission). We should note that the maximum latency (independently of the re-evaluation mechanism) is limited by the PDB of each scenario. In line with the trends observed in Fig. 9(a), Fig. 9(b)-(d) show that the selective proposal significantly reduces the latency under the low and medium intensity scenarios independently of the density. In the high intensity scenario, the standard and selective re-evaluation mechanisms exhibit similar SRO levels due to the smaller PDB and selection windows, and there are hence no noticeable differences in the latency.




a) Selected resource offset b) Latency (low)
c) Latency (medium) d) Latency (high)

Fig. 9. Impact of the re-evaluation mechanisms on the latency: SRO for 100 veh/km (a) and CDF of the latency for low intensity (b), medium intensity (c) and high intensity (d) scenarios with 50 and 100 veh/km.

## VIII. Conclusions

This paper presents and evaluates a novel selective re-evaluation mechanism that improves the performance of the standard 5G NR V2X mode 2 communications. The standard re-evaluation mechanism selects new resources when detecting a potential packet collision. However, many of these collisions ultimately do not happen when the traffic is aperiodic of variable size due to size and latency reselections as well as unutilized reservations. In addition, selecting new resources increases the probability of packet collisions. The proposed selective mechanism addresses these challenges by executing resource replacements only when the vehicle is certain that the collision detected with re-evaluation will occur, which is the

[4] The SRO can have negative values when a resource replacement advances the transmission, which is more likely to occur on resource replacements for retransmissions (Section III.C).

case when a re-evaluation detection is triggered by a reservation for a retransmission of a TB. The selective re-evaluation mechanism is therefore applicable only when NR V2X mode 2 is configured with retransmissions. However, it is important to highlight that two transmissions per TB is the configuration recommended by SAE, and also the NR V2X mode 2 configuration used in this study. The selective re-evaluation proposal reduces the number of resource replacements, increases the reliability of NR V2X mode 2 and reduces its latency (in particular for larger PDB values) under the presence of aperiodic traffic of variable size. The selective re-evaluation mechanism has been evaluated in a highway scenario, but similar trends are expected in urban scenarios since the impact of the selective re-evaluation mechanism ultimately depends on the load perceived by vehicles (i.e. the number of packet collisions detected).

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