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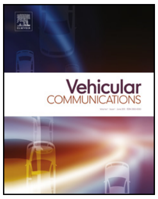

A comparative analysis of the semi-persistent and dynamic scheduling schemes in NR-V2X mode 2

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A B S T R A C T

Over the last years, the evolution of Vehicle-to-Everything (V2X) services from basic safety-related to enhanced V2X (eV2X) applications prompted the development of the 5G New Radio (NR)-V2X technology. Standardized by the Third Generation Partnership Project (3GPP) in Release 16, NR-V2X features a distributed resource allocation mode, known as Mode 2, that allows vehicles to autonomously select their transmission resources employing a Semi-Persistent Scheduling (SPS) or a Dynamic Scheduling (DS) scheme. The SPS approach relies on the periodic reservation of resources, whereas the DS scheme is a reservation-less solution that forces the selection of new transmission resources for every generated message. 3GPP standards do not indicate under which conditions each scheduling scheme should be used. In this context, this study analyzes and compares the performance of SPS and DS under different traffic types and Packet Delay Budget (PDB) requirements. Simulation results demonstrate that the SPS scheme represents the best solution for serving fixed size periodic traffic, whereas DS is more adequate for aperiodic traffic (of fixed or variable size). The study shows that the superiority of DS over SPS becomes more evident when tighter PDB requirements are considered, and that the performance of the DS scheme is independent of the PDB. It is also demonstrated that an adaptive scheduling strategy, which allows vehicles to select the scheduling scheme that best suits the type of generated traffic, is the best solution in mixed traffic scenarios where fixed size periodic traffic and variable size aperiodic traffic sources coexist.

1. Introduction

As the evolution of Intelligent Transportation Systems (ITS) has progressively shifted towards connected and automated driving, Vehicle-to-Everything (V2X) communications have attracted a great deal of attention from both the academic and the industrial world, emerging as a key technology to improve road safety and transportation efficiency. To this end, the Third Generation Partnership Project (3GPP) introduced in Release 14 the first Cellular V2X (C-V2X) technology, known as LTE-V2X. The LTE-V2X design has been tailored to support basic safety-related applications in both in-coverage and out-of-coverage scenarios. In the latter case, the LTE-V2X Mode 4 distributed resource allocation mode allows vehicles to autonomously select their transmission resources employing a Semi-Persistent Scheduling (SPS) scheme. Over the last years, several works have analyzed the performance of LTE-V2X Mode 4 and the SPS scheme [1–3], shedding light on the inefficiencies that characterize its Medium Access Control (MAC) sublayer design. As a matter of fact, the SPS scheme relies on the periodic reservation of transmission resources and it falls short when variable size aperiodic messages are considered [4,5].

The advent of more sophisticated enhanced V2X (eV2X) services, such as cooperative perception and maneuver coordination [6], prompted the development of the 5G New Radio (NR)-V2X technology under Release 16. NR-V2X is characterized by a novel

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physical (PHY) layer design and new MAC sublayer features expected to improve the performance and capabilities of C-V2X communications [7]. At MAC sublayer, 3GPP has introduced NR-V2X Mode 2, a distributed resource allocation mode designed to complement Mode 4, its LTE-V2X predecessor. NR-V2X Mode 2 features a new mandatory re-evaluation mechanism, which has been thoroughly analyzed in [8], and includes both an SPS and a Dynamic Scheduling (DS) scheme. The SPS scheme has been inherited from LTE-V2X specifications with minor modifications, whereas the DS scheme is a new reservation-less solution that forces the selection of new transmission resources for every generated message. However, 3GPP standards do not provide any indication about the circumstances under which the SPS or DS scheme should be used [9].

As of today, few papers investigated the performance of the SPS scheme in NR-V2X Mode 2 [10–12], showing that the effective dissemination of aperiodic traffic cannot be guaranteed, especially when the size of the generated messages is not fixed. In this regard, novel Artificial Intelligence (AI)-based solutions [13,14] and alternative techniques [15,16] have been proposed to overcome the SPS design limitations.

On the other hand, no work has comprehensively analyzed the DS scheme yet. To the authors' knowledge, the only studies that concentrated on the comparison between the SPS and DS schemes are [17] and [18], although these works assumed fixed size messages, constant latency requirements, and did not consider the re-evaluation mechanism, which is mandatory in NR-V2X Mode 2.

In this context, the distinctive intent of this work is to provide clear guidelines to identify under which traffic types the SPS or DS schemes should be utilized. In this study, we consider periodic and aperiodic traffic of fixed or variable message size following the 3GPP evaluation guidelines [20]. Another important contribution of this study is that it also compares, for the first time, the two scheduling schemes under different latency or Packet Delay Budget (PDB) requirements. This is relevant since eV2X applications that will be supported by NR-V2X Mode 2 are characterized by a wide range of latency requirements [19], and the PDB identifies an upper bound to the maximum latency that a message can experience in NR-V2X Mode 2. The SPS and DS performance is also compared in mixed traffic scenarios, where fixed size periodic traffic and variable size aperiodic traffic sources coexist within the same NR-V2X system. In this case, a novel Adaptive Scheduling (AS) strategy that allows vehicles to select the scheduling scheme which best suits the type of generated traffic is put forth. It is demonstrated that the proposed adaptive strategy yields the best performance for all traffic types and PDB requirements. The main findings of this study are the following:

- the performance of the SPS scheme can significantly deteriorate in the presence of aperiodic traffic, in particular with increasingly stringent PDB constraints;
- conversely, the performance of the DS scheme is independent of the PDB requirements, no matter what traffic type is considered;
- the SPS scheme represents the best solution for serving fixed size periodic traffic, provided that the reservation periodicity matches the traffic generation period;
- the DS scheme is the best option for fixed or variable size aperiodic traffic. The superiority of DS over SPS becomes more evident when increasingly stringent PDB requirements are examined;
- the AS strategy consistently achieves better performance than the SPS and DS schemes under mixed traffic scenarios.

The remainder of this paper is organized as follows: Section 2 provides an overview of the most relevant NR-V2X Mode 2 features, with a special focus on the SPS and DS schemes. Section 3 puts forth a qualitative analysis of the NR-V2X Mode 2 MAC sublayer, highlighting the impact of different traffic types and PDB choices on the collision probability. Section 4 describes the simulation environment, the traffic models, and the metrics considered in this study. Section 5 numerically analyzes the PDB impact on the performance of SPS and DS, and Section 6 reports an exhaustive comparison between the two scheduling schemes. Section 6 also introduces and evaluates the proposed adaptive scheduling strategy. Finally, Section 7 summarizes the main conclusions of this study.

2. Overview of NR-V2X mode 2

NR-V2X introduces a broad set of MAC sublayer and PHY layer improvements with the aim of supporting the eV2X use cases defined in [6].

At PHY layer, the information is transmitted using a Cyclic Prefix (CP) - Orthogonal Frequency Division Multiplexing (OFDM) waveform that supports different SubCarrier Spacing (SCS) settings. The SCS values supported in NR-V2X are $2^{\mu} \times 15$ kHz, where μ is the OFDM numerology index, $\mu = 0, 1, 2$. These values correspond to an SCS of 15, 30 and 60 kHz, respectively. It is worth pointing out that all the users operating within a given NR-V2X system must employ the same OFDM numerology. In NR-V2X, transmission resources are organized on a time-frequency grid in which the smallest time and frequency units are the time slot and the Resource Block (RB). The duration of the time slot is defined as $t_s = 2^{-\mu}$ ms. Depending on the adopted OFDM numerology, t_s is equal to $1, 0.5$, or 0.25 ms. In the frequency domain, an RB consists of 12 adjacent OFDM subcarriers, and it is 180, 360, or 720 kHz wide depending on the employed SCS. A group of adjacent RBs within the same time slot defines a subchannel, which represents the smallest time-frequency unit for data transmission and reception. According to the standard [21], a subchannel can consist of $10, 12, 15, 20, 25, 50, 75$, or 100 RBs.

When a new message is generated, its content is encoded using Low Density Parity Check (LDPC) codes and encapsulated within a Transport Block (TB). In NR-V2X, the transmission of each TB is associated with dedicated Sidelink Control Information (SCI). The SCI content is organized in two different stages, and it includes relevant information for the correct decoding of the TB such as the adopted Modulation and Coding Scheme (MCS). Specifically, the modulation of the TB ranges from QPSK to 256QAM, whereas it is limited to QPSK in the SCI case. The transmission of the first stage and second stage SCI is performed on the same RBs employed by the associated TB, during the same time slot. Depending on the message size, the TB plus SCI transmission occupies a variable number of subchannels.

The 3GPP also devoted significant efforts at the MAC sublayer to develop a new resource allocation mode, known as NR-V2X Mode 2. In NR-V2X Mode 2, vehicles employ either an SPS or a DS scheme for selecting the subchannel(s) that will accommodate the TBs transmission. Vehicles using the SPS scheme periodically reserve the selected subchannel(s) for a number of reselection counter, C_{resel}, consecutive transmissions. The time period between consecutive reservations is called Resource Reservation Interval (RRI), and NR-V2X supports any RRI value in the $\{0, [1{:}1{:}99], [100{:}100{:}1000]\}$ ms range, where in the $[x{:}y{:}z]$ notation, x denotes the minimum allowed value, z the maximum, and y the incremental step between consecutive values. Vehicles employ the SCI to broadcast the adopted RRI configuration and inform neighboring vehicles about their next reservation. Depending on the selected RRI, the value of the reselection counter is set as follows: if RRI ≥ 100 ms, C_{resel} is randomly set between 5 and 15; otherwise, C_{resel} is randomly selected in the $[5 \cdot C, 15 \cdot C]$ interval,

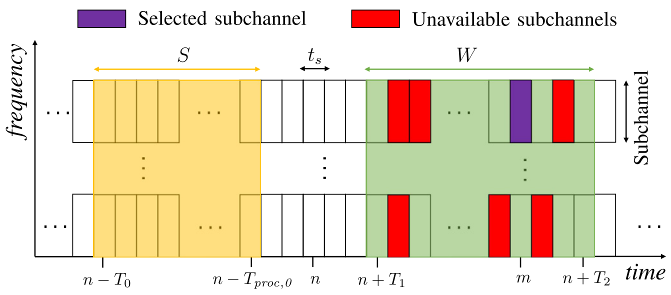

Fig. 1. Resource reselection in NR-V2X Mode 2.

$C = 100/\max(20, \text{RRI})$. After every transmission, the value of the reselection counter is decremented by one; when $C_{resel} = 0$, the ego-vehicle selects new subchannels with probability $1 - P$, where P is the keep probability, $P \in [0, 0.8]$. On the other hand, vehicles using the DS scheme select new subchannels every time a new message is generated, and are not allowed to place any reservation. In other words, DS is the reservation-less variant of the SPS scheme[3] which sets $C_{resel} = 1$ and $P = 0$.

Despite being characterized by a totally different reservation policy, the SPS and DS schemes employ the same resource reselection process (illustrated in Fig. 1) for selecting new subchannels. Let us call n the time slot at which the ego-vehicle generates a new message and triggers a resource reselection. First, the ego-vehicle builds a list of the candidate subchannels that lie within the so-called selection window, W. The selection window extends from slot $n + T_1$ to slot $n + T_2$, where T_1 is smaller than $3, 5, 9$ slots for a SCS of $15, 30, 60$ kHz, and $T_2 \leq$ PDB. Then, the ego-vehicle removes the unavailable subchannels from the candidates' list. A subchannel is considered unavailable if it has already been reserved by the SCI of a neighboring vehicle during the ego-vehicle's sensing window, S. Unavailable subchannels are excluded from the candidates' list only if the associated SCI is received with a Reference Signal Received Power (RSRP) larger than a pre-configured threshold. The sensing window is the time interval identified by the $[n - T_0, n - T_{proc,0}]$ range of slots. According to the standard, $T_{proc,0}$ is equal to 1 slot when the SCS is 15 or 30 kHz, and equal to 2 slots when the SCS is 60 kHz. The value of T_0 can be set to a number of slots equivalent to either 1100 ms or 100 ms. The ego-vehicle also excludes all the subchannels that lie on a time slot in which it was previously transmitting. If the ego-vehicle was transmitting during the sensing window, e.g., at slot s, it could not sense the reservations announced by its neighbors during the same time slot due to its half-duplex limitations. Therefore, all the subchannels located at slot $s + \text{RRI}$ within W are considered unavailable from the ego-vehicle and removed from the candidates' list. The RSRP threshold is increased by 3 dB, and the resource reselection process is re-executed, until the list of candidate subchannels contains at least the β% of the subchannels included in W. Depending on the priority of the TB, β can be set to $20, 35$, or 50. Once the list of candidate subchannels has been determined, the ego-vehicle randomly selects a number of adjacent subchannels (e.g., at slot m in Fig. 1) able to accommodate the transmission of the TB and the associated SCI during the same time slot.

In NR-V2X Mode 2, 3GPP has introduced the re-evaluation mechanism, a new mandatory feature designed to guarantee a more reliable message delivery. The re-evaluation mechanism forces the ego-vehicle to keep monitoring the status of its selected resources before transmitting the TB. The intention is to detect potential collisions that were not identified during the resource reselection process. It is important to highlight the difference between selected and reserved resources: reserved resources are subchannels that a vehicle has selected and reserved for its future transmissions using the SCI. On the other hand, selected resources are subchannels that have not been reserved through the SCI broadcasting. For example, the subchannel(s) employed at the end of a resource reselection are selected resources. Since selected resources cannot be announced before being utilized, they are characterized by a higher collision probability.

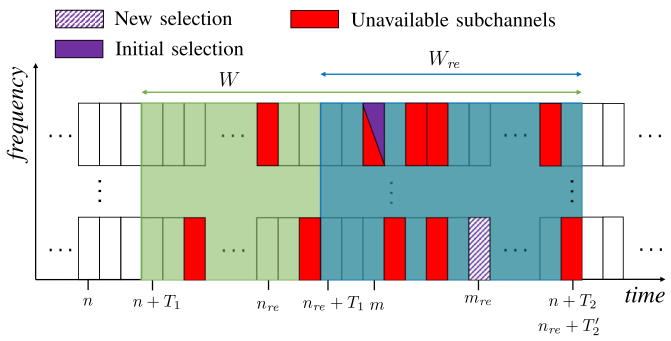

Fig. 2. Re-evaluation mechanism in NR-V2X Mode 2.

Following the notation of Fig. 1, the functioning of the re-evaluation mechanism is illustrated in Fig. 2. Let us assume that the ego-vehicle has generated a message at slot n and that, after performing a resource reselection, it has selected the subchannel at slot m. As the resources selected during a resource reselection cannot be announced beforehand, the re-evaluation mechanism forces the ego-vehicle to re-execute the resource reselection process at slot $n_{re} = m - T_3$. According to 3GPP standards, T_3 is set equal to $3, 5, 9$ slots for an SCS of $15, 30, 60$ kHz, and it represents the time needed to re-execute the reselection process. The ego-vehicle defines a new selection window, W_{re}, that extends from slot $n_{re} + T_1$ to slot $n_{re} + T_2' = n + T_2$ and partially overlaps with the selection window W initially defined at slot n. After removing the unavailable subchannels from W_{re}, the ego-vehicle builds a new list of candidate subchannels. As illustrated in Fig. 2, if the initial selection at slot m is now excluded from the candidates' list due to, e.g., a previously undetected reservation from a neighboring vehicle, the re-evaluation mechanism forces the selection of a new subchannel, located at slot m_{re} in Fig. 2, to avoid the imminent collision.

3. NR-V2X mode 2: MAC analysis

This Section analyzes the functioning of the NR-V2X Mode 2 MAC sublayer. The goal is to shed light on the impact that different traffic types and PDB requirements have on the operation of the SPS and DS schemes.

We begin by observing that, during the resource reselection process, collisions may occur when the selection windows of two or more vehicles overlap and the vehicles end up selecting the same subchannels. This type of collision is unavoidable, regardless of the adopted scheduling scheme, since selected resources cannot be announced before being employed to transmit a TB and the associated SCI; this type of collision cannot be avoided by the re-evaluation mechanism too, as discussed in [8]. This situation is illustrated in Fig. 3(a), where two vehicles, v_1 and v_2, perform a resource reselection and their selection windows, W_1 and W_2, partially overlap. If the two vehicles select the same resources in the overlapping region, a collision will occur. Note that, in the SPS case, the collision will persist for a number of consecu-

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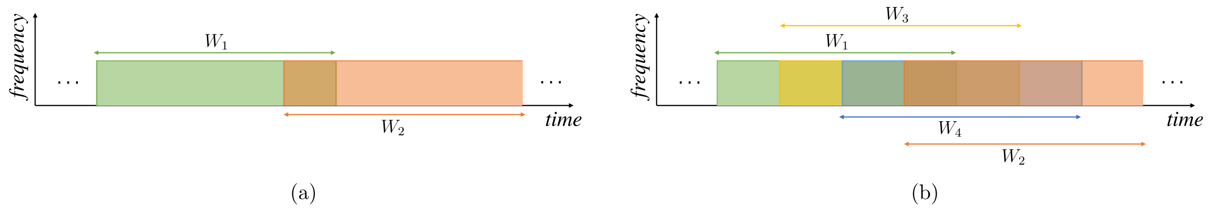
[3] The DS scheme can only reserve resources for the re-transmissions of a TB. However, re-transmissions are not mandatory in NR-V2X Mode 2 and are not considered in this work.



(a)

(b)

Fig. 3. Collision probability associated with resource reselections.

tive transmissions if the two vehicles generate messages with the same periodicity and employ the same RRI.

Collisions may occur any time a vehicle performs a resource reselection for selecting new subchannels. As a result, the larger the number of resource reselections, the higher the collision probability, as Fig. 3(b) suggests. In this figure, two additional vehicles, v_3 and v_4, perform a resource reselection and their selection windows, W_3 and W_4, overlap with W_1 and W_2. It follows that the number of potentially interfering vehicles grows from 2 to 4, therefore increasing the collision probability.

3.1. Impact of different traffic types

When vehicles generate fixed size periodic messages and reserve resources with the same periodicity, they perform a resource reselection only when the reselection counter expires, i.e., $C_{resel} = 0$. We term such an event counter reselection. In the SPS case, the number of counter reselections depends on the value of the keep probability P and on the average C_{resel} counter value. On the other hand, with the DS scheme, a counter reselection is triggered every time a new message is generated, regardless of the traffic type.

When the message size, or the inter-arrival time between messages, is not constant, the SPS scheme experiences additional size and latency reselections. These additional resource reselections deteriorate the scheduling capability of the SPS scheme, as explained next:

- A size reselection occurs when the generated message does not fit the current reservation size and forces the reselection of a larger number of subchannels. A size reselection is exemplified in Fig. 4, where the ego-vehicle generates a 200 bytes long message at slot s_{g_1}, transmits it in the selected subchannel at slot s_{r_1} and broadcasts the associated SCI to reserve the same subchannel after RRI slots, at slot s_{r_2}. However, the next message generated by the ego-vehicle, at slot s_{g_2}, is 400 bytes long and it does not fit in the reservation at slot s_{r_2}. Therefore, the ego-vehicle is forced to perform a resource reselection, select a larger number of subchannels at slot s_{r_3}, and leave the reservation at slot s_{r_2} unutilized.
- A latency reselection is triggered when the reserved subchannel(s) do not satisfy the latency requirements of the generated message, i.e., its PDB. Latency reselections can occur only if the adopted RRI is larger than the PDB of the generated messages, i.e., RRI > PDB. In Fig. 4, after transmitting the TB at slot s_{r_3}, the ego-vehicle reserves the same subchannels after RRI slots, at slot s_{r_4}. Next, the ego-vehicle generates a 200 bytes long message at slot s_{g_3} whose latency limit is identified by the s_{lim} slot. Since $s_{lim} < s_{r_4}$, the reservation at slot s_{r_4} cannot satisfy the PDB of the generated message, thus forcing the reselection of new subchannels able to accommodate the message transmission within its latency limit. As a result, the ego-vehicle selects a new subchannel at slot s_{r_5}, $s_{r_5} < s_{lim}$, and leaves the reservation at slot s_{r_4} unutilized.

Size and latency reselections cause vehicles to perform additional resource reselections before the depletion of the reselection counter, and have a negative impact on the SPS performance. As previously discussed, the collision probability increases with the number of reselections. Conversely, neither size nor latency reselections occur in the DS scheme, as the ego-vehicle performs a counter reselection for each newly generated TB. Table 1 summarizes the occurrence conditions of the different reselection types when both the SPS and the DS scheme are considered.

When investigating the SPS behavior, a further detrimental phenomenon to consider is that of unutilized reservations, which occur when previously reserved subchannels are not employed by the ego-vehicle for transmitting any TB. Unutilized reservations always occur after a size or latency reselection: as exemplified in Fig. 4, the subchannel(s) initially reserved at slots s_{r_2} and s_{r_4} do not accommodate any message transmission. Fig. 4 additionally reveals that reserved subchannels can be left unutilized even when no size or latency reselections take place. These unutilized reservations occur when the employed RRI is lower than the PDB of the generated messages, i.e., RRI < PDB. After employing the selected resources at slot s_{r_5} for transmitting the TB and the associated SCI, the ego-vehicle reserves the same subchannel after RRI slots, at slot s_{r_6}. However, the ego-vehicle does not generate any message until slot s_{g_4}, with $s_{g_4} > s_{r_6}$. Therefore, the ego-vehicle is forced to leave the reservation at slot s_{r_6} unutilized and to transmit the generated message at slot s_{r_7}. Note that the unutilized reservation at slot s_{r_6} does not allow the ego-vehicle to broadcast the corresponding SCI and announce the reservation of the same subchannel at slot s_{r_7}, thus increasing the collision probability. Moreover, observe that unutilized reservations cannot be included by neighboring vehicles in their list of candidate subchannels, which have a reduced pool of candidates wherefrom they select their transmission resources during a resource reselection. Such a waste of system capacity translates into a higher collision probability.

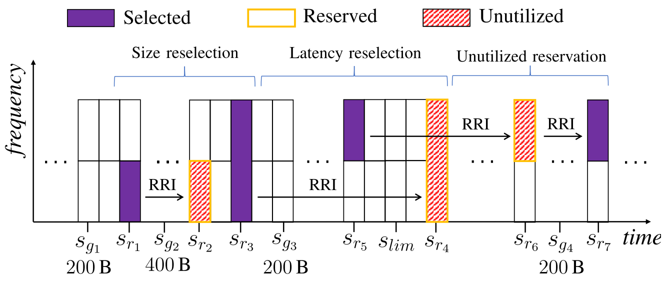


Fig. 4. Impact of different traffic types on NR-V2X Mode 2.

Table 1
Occurrence conditions of different reselection types.

	Counter reselection	Size reselection	Latency reselection
SPS	$C_{resel} = 0$, depends on P	TB size larger than reservation size	$RRI > PDB$
DS	Every TB	Never	Never

3.2. Impact of the PDB

As reported by 3GPP in [19], future eV2X applications will be characterized by a wide spectrum of latency requirements. For instance, the maximum tolerated end-to-end latency will range from 3 ms for emergency trajectory alignment applications to 500 ms for lower priority platooning-related reporting. In this Section, we concentrate on the impact that different latency requirements have on the SPS and DS operation. In NR-V2X Mode 2, the latency requirement of the message is mapped into the PDB, which identifies the upper bound to the latency that a message can experience. We should also recall from Section 2 that the width of the selection window is limited by the T_2 parameter, and $T_2 \leq$ PDB. Unless otherwise stated, we assume that all vehicles employ the same PDB and that $T_2 =$ PDB in the rest of this work.

3.2.1. Dynamic scheduling

With DS, vehicles trigger a counter reselection for every generated message and do not reserve any resources. Due to the lack of reservations, vehicles performing a resource reselection blindly assume that all the subchannels included in their selection window are available, and randomly select a sufficient number of subchannels able to accommodate the message transmission. If we model the selection window as an $N_f \times N_t$ grid, where N_f indicates the number of subchannels on the frequency axis and N_t the number of slots in W, we can conclude that the DS scheme behaves as a multichannel slotted Aloha access strategy. When a new message is generated, it is transmitted on one (or more) randomly selected subchannels out of N_f, during a single time slot.

Based on the Aloha-like assumption, we analytically derive the PDB impact on the DS performance in this Subsection. Let us assume that vehicles generate traffic with an overall average rate λ messages/s, no matter what traffic type is considered. Accordingly, the average number of messages that are generated during a slot of duration t_s is approximately

$$G \simeq \lambda \cdot t_s. \tag{1}$$

Due to the random selection of resources that characterizes the DS scheme, the transmissions of all the messages generated during a generic slot are uniformly distributed within the selection window W. Therefore, a fraction of G given by

$$G_s \simeq \frac{G}{N_t} \tag{2}$$

is poured on the generic slot. However, this term adds to $N_t - 1$ analogous contributions originated during the previous $N_t - 1$ slots. As a result, the average number of messages that are transmitted on every selection window slot is approximated by:

$$G_s + \sum_{i=1}^{N_t-1} G_s = \sum_{i=1}^{N_t} G_s \simeq N_t \cdot \frac{G}{N_t} = G. \tag{3}$$

This reasoning reveals that the number of messages transmitted on every slot does not depend on the width N_t of the selection window. In other words, the collision probability that characterizes the DS scheme, which is a function of G and of the average message size, is independent of the PDB, as it will be numerically demonstrated in the following sections. It is worth highlighting that the DS scheme operation does not depend on the PDB also when only a fraction of vehicles adopts the DS scheme. In this case, vehicles employing the DS scheme randomly select resources over a smaller portion of the selection window, excluding the reservations received from their neighbors.

3.2.2. Semi-persistent scheduling

With SPS, the resource reselection process is not random as in the DS case, but strives to avoid the selection of subchannels already occupied by other vehicles. When the SPS scheme is examined, more stringent latency requirements (i.e., a smaller PDB) and the associated reduction of the selection window width have a three-fold effect. First, a smaller PDB lowers the number of available subchannels in W. As a result, vehicles that trigger a resource reselection during the same time slot have a larger probability of selecting the same subchannels and generate a collision. Second, a shorter selection window reduces the number of potentially interfering vehicles (i.e., the number of vehicles whose selection windows overlap), accordingly reducing the collision probability. As it will be demonstrated by simulation results, these two effects cancel out.

Third, when the RRI does not match the inter-arrival time between messages, a smaller PDB reduces the probability that reserved subchannels satisfy the latency requirements of the generated messages. Hence, more latency reselections may occur and the collision probability increases.

4. Simulation environment

The operation and performance of the SPS and DS schemes have been evaluated employing the MoReV2X simulator [22]. The simulator features an accurate implementation of NR-V2X Mode 2 which adheres to the 3GPP specifications and evaluation guidelines [20].

The examined scenario consists of a 5 km long highway segment with 3 lanes per driving direction. To avoid border effects, performance metrics are collected only in the central 2 kilometers. The highway trunk is populated considering three different vehicular density values: 50, 120, and 300 vehicles/km. The vehicular density is computed considering both driving directions and the total number of lanes. The speed of the vehicles is 70 km/h.

In all simulations, the OFDM numerology is $\mu = 1$. Accordingly, SCS $= 30$ kHz and $t_s = 0.5$ ms. NR-V2X radios are configured to operate on a 20 MHz channel in the 5.9 GHz ITS band and employ 12 RBs long subchannels. As a result, the total number of available subchannels in every time slot is 4. TBs are transmitted with a 16QAM-0.5 MCS. Following the indications reported in [23], the transmission power is set to 23 dBm and the receiver sensitivity to -103.5 dBm. Pathloss and shadowing are implemented using the models reported in [20]. To take into account the fast-fading impairments which affect the TB and SCI PHY layer performance, we leverage the BLock Error Rate (BLER) curves reported in [24] and [25], respectively. At the MAC sublayer, T_0 is set to a number of slots equivalent to 1100 ms, the initial RSRP threshold is equal to -128 dBm, and $\beta = 20\%$. In SPS, the keep probability is $P = 0$. The most relevant simulation parameters are summarized in Table 2.

4.1. Traffic models

To generation of TBs at each vehicle is modeled considering three different traffic types, namely:

- Periodic traffic, Fixed size (PF): vehicles periodically generate constant size messages of 190 bytes. The generation period is $T = 100$ ms and corresponds to the periodicity value recommended in the 3GPP *Periodic traffic Model 1* reported in [20]. When the SPS scheme is employed, vehicles reserve their resources according to the traffic periodicity and set RRI $= T =$ 100 ms.
- Aperiodic traffic, Fixed size (AF): in this case, the inter-arrival time between messages, τ, is a random variable defined as:

Table 2
Simulation parameters.

Parameter	Values
Traffic density	50, 120, 300 vehicles/km
Highway length	5 km
Number of lanes	6 (3 per driving direction)
Vehicles' speed	70 km/h
OFDM numerology μ	1
SCS	30 kHz
Time slot duration t_s	0.5 ms
Channel bandwidth	20 MHz
Subchannel size	12 RBs
Available subchannels	4
MCS	16QAM-0.5
Transmission power	23 dBm
Receiver sensitivity	-103.5 dBm
RSRP threshold	-128 dBm
Keep probability P	0

$$\tau = c + r, \tag{4}$$

where c is a constant term and r is an exponentially distributed random variable with mean value $\bar{r} = c = 50$ ms. It follows that the average inter-arrival time is 100 ms. The description of τ adheres to the 3GPP *Aperiodic Traffic Model 1* included in [20]. The message size is equal to 200 bytes. When AF traffic is considered and vehicles employ the SPS scheme, the RRI is set equal to the minimum inter-arrival time between messages, i.e., RRI $= c = 50$ ms. The study in [10] has shown that such a setting, termed minimum RRI strategy, guarantees the best performance with respect to alternative solutions.

- Aperiodic traffic, Variable size (AV): this type of traffic is characterized by the same description of the inter-arrival time as the AF model. The message size is randomly selected in the [200:200:1200] bytes range, following the *Aperiodic Traffic Model 1* indications provided by 3GPP in [20]. Also in this case, vehicles adopting the SPS scheme reserve resources using the minimum RRI strategy and set RRI $= 50$ ms.

According to the adopted MCS, the set of message size values considered in this work, i.e., $[190, 200, 400, 600, 800, 1000, 1200]$ bytes, is accommodated over $[1, 1, 2, 3, 3, 4, 4]$ subchannels, respectively. This allows to conclude that PF and AF traffic occupy an average number of subchannels equal to 1, whereas AV traffic occupies an average number of 2.83 subchannels.

We analyze and compare the performance of the SPS and DS schemes in two different scenarios: single traffic and mixed traffic. In the single traffic scenario, all vehicles employ the same traffic model (PF, AF, or AV). In the mixed traffic scenario, a percentage Δ of vehicles generates PF traffic, whereas the remaining $(100 - \Delta)\%$ generates AV traffic. Vehicles do not change the type of generated traffic during the simulation.

4.2. Metrics

The performance of SPS and DS is assessed considering an exhaustive set of metrics. In accordance with 3GPP evaluation guidelines [20], the system-level performance of NR-V2X Mode 2 is analyzed considering the Packet Reception Ratio (PRR). The PRR is defined as the average fraction of correctly decoded TBs with respect to the total number of transmitted TBs. In this work, the PRR is reported as a function of D, the distance between the transmitting and the receiving vehicle. An additional performance metric is the Packet Collision Ratio (PCR), which measures the fraction of TBs that are lost due to collisions with respect to the total number of transmitted TBs. A TB is lost in a collision when the received Signal-to-Interference-plus-Noise Ratio (SINR) is not sufficient for its correct decoding. Also the PCR is reported as a function of the transmitter-receiver distance D.

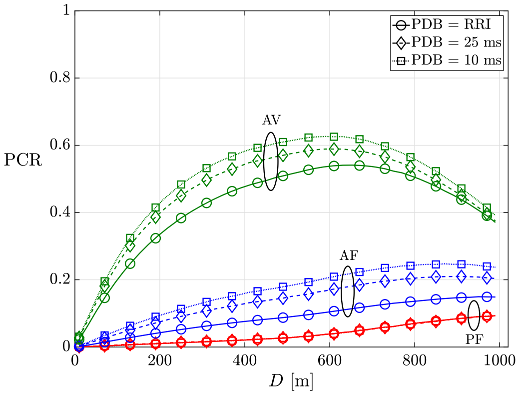


Fig. 5. SPS scheme: PCR as a function of D.

A further relevant metric is the Channel Busy Ratio (CBR), a physical layer indicator used to estimate the channel load. At slot n, the CBR is measured as the fraction of subchannels whose Received Signal Strength Indicator (RSSI) is larger than a threshold in the $[n - 100 \cdot 2^{\mu}, n - 1]$ range of slots. In this work, the RSSI threshold is -88 dBm.

The results presented in this work also include a dedicated set of metrics that capture the impact of different traffic types on the operation of the SPS and DS schemes, namely:

- Size Reselections Ratio (SRR): fraction of TBs that triggered a size reselection with respect to the total number of transmitted TBs.
- Latency Reselections Ratio (LRR): fraction of TBs that triggered a latency reselection with respect to the total number of transmitted TBs.
- Unutilized Reservations Ratio (URR): ratio between the number of reservations that are left unutilized and the total number of reservations. The URR metric does not take into account the reservations that are left unutilized after a size or latency reselection.

5. Impact of the PDB on the SPS and DS schemes

Before delving into the comparison between SPS and DS, this Section elaborates on the impact that the PDB has on the collision probability.

Fig. 5 reports the PCR of the SPS scheme as a function of the average transmitter-receiver distance D in the single traffic scenario, when the PF, AF, and AV traffic models are examined. The vehicular density is set to 120 veh/km and three representative PDB values are taken into consideration: a PDB value which coincides with the RRI of the SPS scheme, i.e., PDB $=$ RRI, PDB $= 25$ ms, and PDB $= 10$ ms. In [19], 25 ms and 10 ms represent the maximum end-to-end latency required by the lowest and the highest degree of automation in cooperative driving applications. In the PDB $=$ RRI case, the PDB is set to 100 ms when PF traffic is examined, whereas it is equal to 50 ms for the AF and AV traffic models. Note that the PDB $=$ RRI choice has been employed in many existing studies, e.g., [2,10,13].

Fig. 5 reveals that the PCR curves perfectly overlap for the three different PDB values when considering PF traffic, showing that the collision probability is not affected by increasingly stringent PDB requirements. It was qualitatively observed in Subsection 3.2 that a smaller PDB reduces the amount of available subchannels included in the selection window, but at the same time decreases the number of vehicles whose selection windows overlap. Here,

Table 3
CBR Values, Single Traffic Scenario.

	50 veh/km	120 veh/km	300 veh/km
PF	0.09	0.22	0.47
AF	0.09	0.22	0.45
AV	0.23	0.46	0.79

Table 4
SPS Scheme, Single Traffic Scenario - LRR.

	PDB = RRI	PDB = 25 ms	PDB = 10 ms
PF	0	0	0
AF	0	0.48	0.77
AV	0	0.48	0.77

we numerically demonstrate that these two effects cancel out for PF traffic, since the PCR is not affected by the PDB.

When the AF traffic model is considered, Fig. 5 shows that the PCR performance deteriorates as tighter PDB requirements are considered. The same trend is observed with AV traffic. For a given vehicular density, we should note that AV traffic is characterized by a larger CBR compared to PF and AF traffic models, since the average number of subchannels occupied by AV traffic is 2.83 times larger. Table 3 reports the CBR values computed for the different vehicular densities and traffic models. As anticipated in Section 3.2, tighter PDB requirements increase the number of latency reselections and accordingly augment the collision probability when the RRI does not match the inter-arrival time between messages. Table 4 reports the values of the LRR metric for the SPS scheme. From Table 4, the upsurging of latency reselections is manifest when the AF and AV traffic types are examined. Note that the LRR increases as more stringent PDB requirements are considered, justifying the PCR deterioration observed in Fig. 5. We should also note that, as the distribution of the inter-arrival time between messages of AF and AV traffic is the same, the LRR metric is coincident in the last two rows of Table 4.

Next, Fig. 6 quantifies the impact of the PDB on the PCR performance of the DS scheme. This figure corroborates the conclusions provided by the MAC sublayer analysis of Subsection 3.2 with simulation results. For each traffic type, more stringent PDB requirements do not affect the collision probability of the DS scheme since the PCR curves referring to the three different PDB choices perfectly overlap.

The independence of DS on the PDB has important implications. According to it, the DS scheme can be used to support V2X applications with a wide range of latency requirements without suffering any performance degradation, regardless of the generated traffic type. On the other hand, the SPS scheme guarantees a similar robustness to PDB variations only when PF traffic is considered. Last, it is worth pointing out that the impact of the PDB on the SPS and DS schemes exclusively depends on the type of generated traffic and not on the vehicular density.

6. SPS and DS performance comparison

This Section compares the performance attained by the SPS and DS schemes under various traffic types and PDB requirements. The evaluation helps identify the conditions under which the two scheduling schemes should be utilized. Based on these findings, this Section introduces and evaluates an adaptive scheduling strategy that allows vehicles to select the scheduling scheme that best suits their generated traffic.

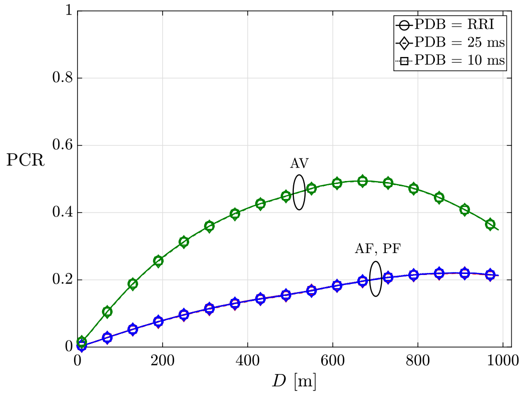


Fig. 6. DS scheme: PCR as a function of D.

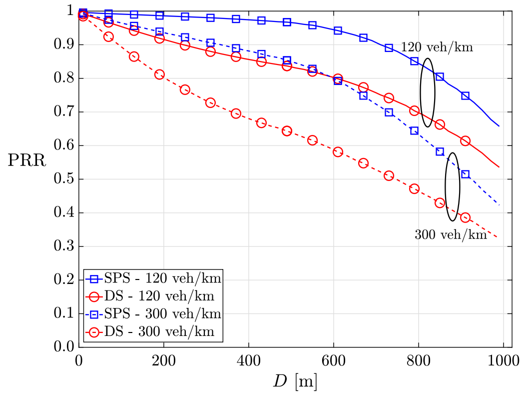


Fig. 7. Single traffic scenario, PF traffic model, PDB = RRI: PRR as a function of D.

6.1. *Single traffic scenario*

We first compare the SPS and DS schemes in the single traffic scenario when the PF, AF, and AV traffic models are separately examined. For each traffic model, the impact of different PDB requirements and channel load levels on the PRR is quantified.

Fig. 7 compares the PRR performance of the SPS and DS schemes as a function of the transmitter-receiver distance D when PF traffic is considered. The PDB is set to 100 ms (PDB = RRI), and two vehicular densities are examined, 120 and 300 veh/km. The former corresponds to CBR = 0.22 and the latter to CBR = 0.47, as reported in Table 3. The figure shows that SPS outperforms the DS scheme at both vehicular densities, and that the performance gap becomes larger as the channel load increases. As a matter of fact, the periodic reservation of resources which characterizes the SPS scheme perfectly suits the dissemination of PF traffic and does not generate any latency reselections (LRR = 0 in Table 4), size reselections, or unutilized reservations. The SRR and URR metrics are reported in Table 5. Since Section 5 demonstrated that the PDB does not have any impact on the SPS and DS performance with PF traffic, Fig. 7 shows the results for only the PDB = RRI choice. To conclude, the SPS scheme is the best approach in NR-V2X mode 2 to support periodic fixed size traffic, no matter how stringent the PDB requirements are.

Next, Fig. 8 compares SPS and DS in the presence of AF traffic for the same vehicular densities of Fig. 7. In Fig. 8(a), the PDB = RRI choice is examined. According to it, PDB = 50 ms for AF traffic. Fig. 8(a) shows that the SPS scheme achieves a better performance than DS only when the vehicular density is 120 km/h, i.e., when the radio channel is lightly loaded. When the vehicular density increases to 300 km/h and the channel load is no longer

Table 5
SPS Scheme, Single Traffic Scenario - SRR, and URR.

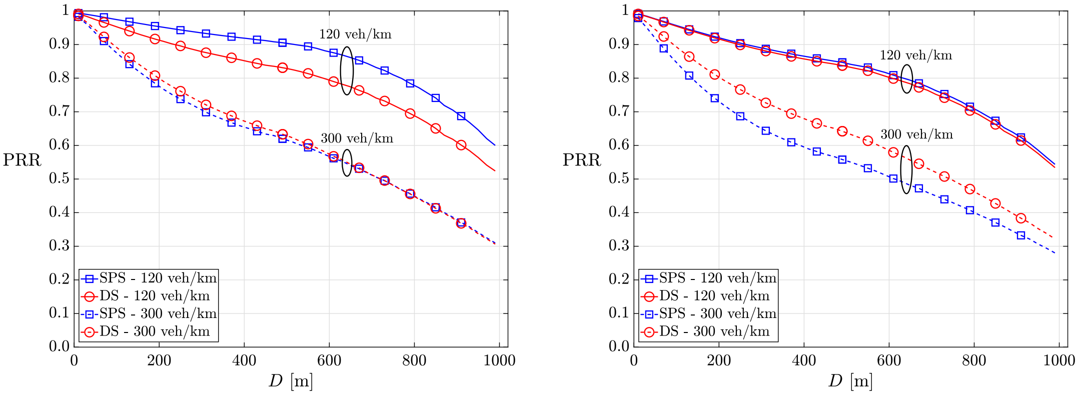
	SRR			URR		
	PDB = RRI	PDB = 25 ms	PDB = 10 ms	PDB = RRI	PDB = 25 ms	PDB = 10 ms
PF	0	0	0	0	0	0
AF	0	0	0	0.47	0.55	0.58
AV	0.07	0.24	0.32	0.47	0.55	0.58

negligible, the PRR performance of the two schemes becomes comparable, with DS attaining slightly better values.

In this setting, the degradation of the SPS performance for increasing channel loads is due to unutilized reservations (URR) only, as both the LRR and SRR metrics are equal to zero (see Tables 4 and 5). When the radio channel is lightly loaded, the fraction of unutilized reservations is not sufficiently large to affect the SPS performance. As the channel load increases, the waste of system capacity associated with unutilized reservations deteriorates the performance of the SPS scheme, which becomes slightly worse than that of the DS scheme. On the other hand, the DS scheme does not experience any latency reselection, size reselection, or unutilized reservation (i.e., LRR = 0, SRR = 0, and URR = 0), since new subchannels are selected for every generated message.

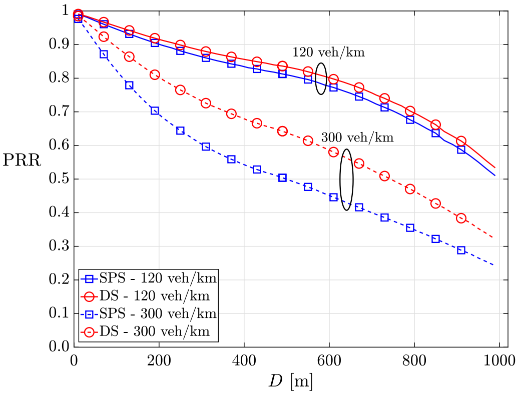
Figs. 8(b) and 8(c) compare the SPS and DS performance considering smaller PDB values, i.e., PDB = 25 ms and PDB = 10 ms. For AF traffic, the performance of the SPS scheme is further deteriorated when more stringent PDB requirements are considered, due to the presence of latency reselections (see Table 4). Recall from Section 3.1 that latency reselections occur when the PDB is smaller than the employed RRI. Conversely, the DS scheme operation is not affected by PDB variations, and the corresponding PRR curves do not modify when moving from Fig. 8(a) to Figs. 8(b)-(c). These results show that DS always attains better or comparable PRR levels than the SPS scheme when vehicles generate AF traffic, independently of the channel load.

In the presence of AV traffic, Fig. 9 compares SPS and DS for the PDB = RRI, PDB = 25 ms, and PDB = 10 ms choices. For AV traffic, the SPS and DS performance is compared reducing the vehicular densities to 50 veh/km and 120 veh/km in order to consider the same CBR values analyzed so far. This is necessary since AV traffic occupies an average number of subchannels which is 2.83 times larger with respect to PF and AF traffic, as discussed in Section 5. When the vehicular density is 50 veh/km (CBR = 0.23), Fig. 9(a) shows that the gap between the SPS and DS curves is greatly reduced with respect to Fig. 8(a). This is the case since the operation of SPS is also affected by size reselections when AV traffic is considered, as shown in Table 5. Size reselections increase the collision probability (see Section 3.1) and further deteriorate the PRR performance of the SPS scheme. Accordingly, DS outper-



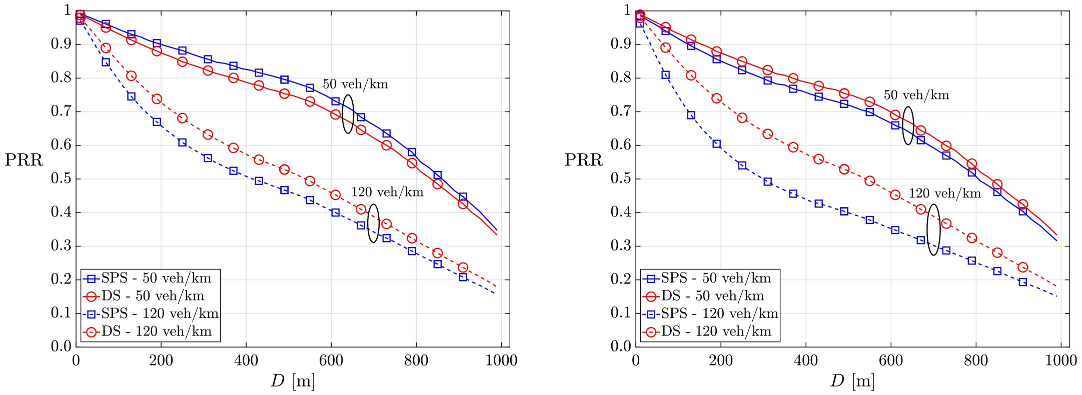
(a) PDB = RRI.

(b) PDB = 25 ms.

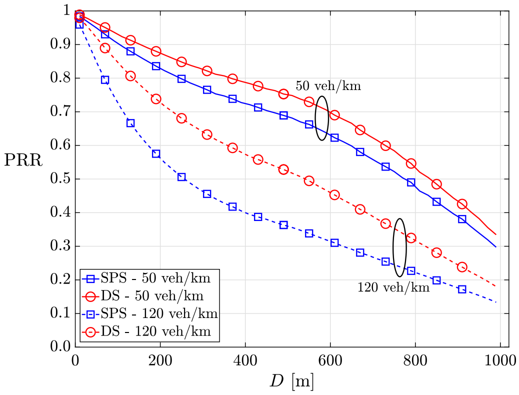


(c) PDB = 10 ms.

Fig. 8. Single traffic scenario, AF traffic model: PRR as a function of D.



(a) PDB = RRI. (b) PDB = 25 ms.



(c) PDB = 10 ms.

Fig. 9. Single traffic scenario, AV traffic model: PRR as a function of D.

forms its SPS counterpart with a larger margin with respect to the AF case when the vehicular density increases to 120 veh/km and CBR = 0.46. The superiority of DS over the SPS scheme becomes even more evident in Figs. 9(b) and 9(c), where the more stringent PDB = 25 ms and 10 ms values are examined. As in the AF traffic case, latency reselections further penalize the performance of the SPS scheme, which attains the smallest PRR values observed so far and is outperformed by the DS solution for all the considered vehicular densities.

The PRR of the DS scheme is independent of the PDB requirements and exclusively depends on the channel load, thus representing the best solution for serving AV traffic in NR-V2X Mode 2.

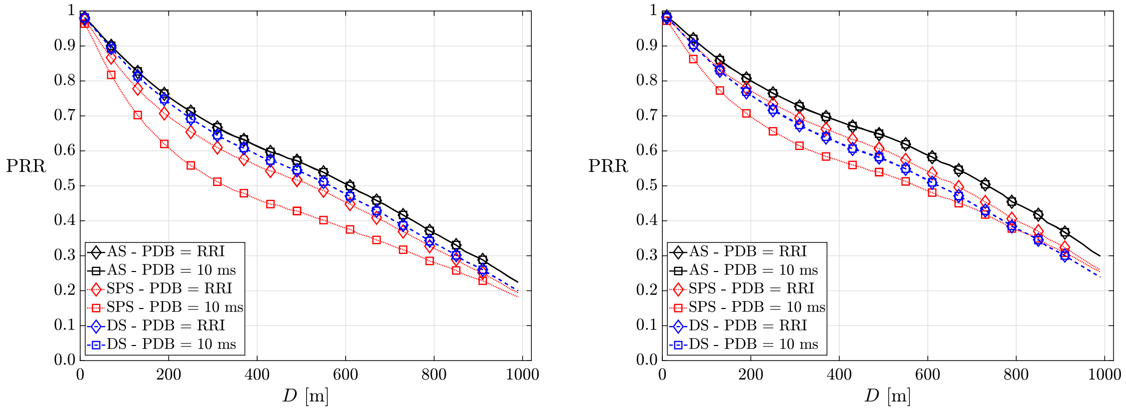
6.2. Mixed traffic scenario and adaptive scheduling

We now compare the SPS and DS schemes in a mixed traffic scenario, where Δ% of the vehicles generates PF traffic and the remaining $(100-\Delta)$% generates AV traffic. In this context, we also propose a novel AS strategy that allows vehicles to select the scheduling scheme that best suits their generated traffic type. Based on the results and conclusions drawn in the previous Subsection, the AS strategy works as follows: if a vehicle generates PF traffic with periodicity T, it employs the SPS scheme with RRI $= T$; if a vehicle generates AV traffic, it uses the DS scheme. Note that the standard does not provide any indication about the circumstances under which the SPS or DS scheme should be used [9], thus allowing the implementation of the adaptive scheduling strategy.

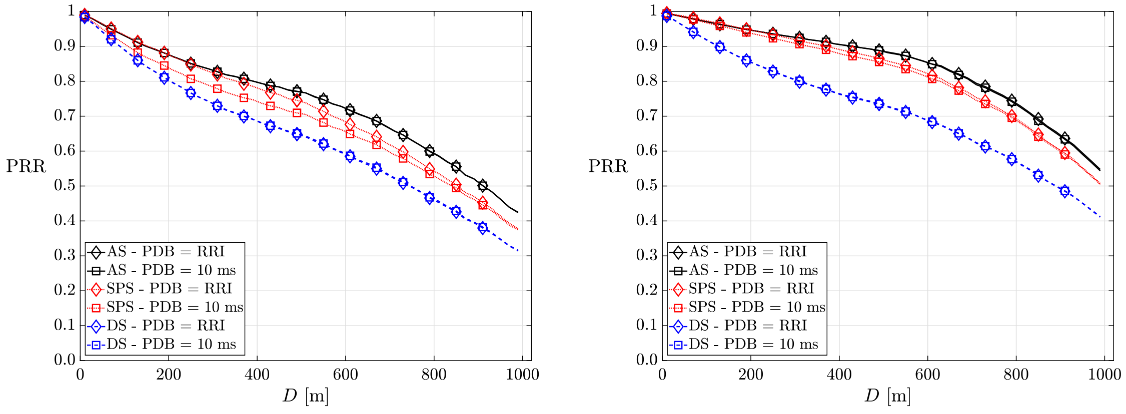
Fig. 10(a) compares the performance of SPS, DS, and AS strategy in the 120 veh/km, $\Delta = 10$% setting for two different PDB choices, i.e., PDB = RRI and PDB = 10 ms. This figure shows that the best PRR performance is attained by the AS strategy, which allows vehicles to employ the most appropriate scheduling scheme based on the type of traffic they generate. Figs. 10(b) to 10(d) show that this trend is maintained for increasing values of Δ and that the AS strategy always achieves the best performance, no matter what value of Δ and PDB is examined.

We should also note that the AS strategy performance does not depend on the PDB. With AS, vehicles generating PF and AV traffic use the SPS and DS schemes, respectively. Therefore, the AS strategy does not experience any latency reselections, size reselections, or unutilized reservations, and its collision probability is not affected by more stringent PDB requirements. The independence of the AS strategy performance on the PDB is aligned with the conclusions of Subsection 3.2.

When we concentrate on SPS and DS, which force vehicles to employ a pre-determined scheduling scheme regardless of the generated traffic type, Fig. 10(a) shows that the DS scheme outperforms its SPS counterpart regardless of the PDB. With $\Delta = 10$%, the majority of the vehicles (90%) generates AV traffic. As a result, the SPS scheme experiences a large number of size reselections and unutilized reservations. In the PDB = 10 ms case, the PRR of the SPS scheme is further deteriorated by the occurrence of latency reselections. The values of the LRR, SRR, and URR metrics which characterize the operation of the SPS scheme in the mixed traffic scenario are reported in Table 6. As already highlighted in Section 6.1, variations in the message size and in the inter-arrival time between messages can significantly deteriorate the SPS performance, whereas they have no impact on the DS scheme. Indeed, the operation of the DS scheme is not affected by the PDB require-



(a) $\Delta = 10\%$. (b) $\Delta = 25\%$.



(c) $\Delta = 50\%$. (d) $\Delta = 75\%$.

Fig. 10. Mixed traffic, 120 veh/km: PRR as a function of D.

ments also in the mixed traffic scenario for any value of Δ, as highlighted from Fig. 10(a) to Fig. 10(d).

As Δ increases, the percentage of vehicles generating AV traffic reduces and so does the number of latency reselections, size reselections, and unutilized reservations experienced by the SPS scheme. Accordingly, SPS can attain better PRR levels with respect to Fig. 10(a). When $\Delta = 25\%$ (Fig. 10(b)), the SPS scheme is able to outperform its DS counterpart in the PDB = RRI case. With the more stringent PDB = 10 ms, DS is still superior to the SPS scheme. When $\Delta = 50\%$ (Fig. 10(c)) and $\Delta = 75\%$ (Fig. 10(d)), PF traffic becomes dominant, and the number of latency reselections, size reselections, and unutilized reservations that characterize the SPS scheme operation significantly reduces (see Table 6). As a result, the SPS scheme outperforms the DS scheme for any PDB choice. The impact of the PDB on the SPS scheme becomes less relevant as the percentage of vehicles generating PF traffic increases. In this regard, recall from Section 5 that the PDB does not affect the SPS scheme operation when all vehicles generate PF traffic (i.e., $\Delta = 100\%$).

The mixed scenario has revealed the importance of adapting the scheduling scheme to the type of generated traffic. In this regard, Figs. 10(a) through 10(d) showed that the AS strategy achieves the best PRR performance regardless of the considered Δ and PDB values. When a pre-determined scheduling scheme is employed, DS is superior to its SPS counterpart only when the majority of vehicles generates AV traffic, due to the impact of unutilized reservations, size reselections and latency reselections on the SPS operation.

7. Conclusions

This paper has presented an accurate and exhaustive comparison between the SPS and DS schemes included in NR-V2X Mode 2, providing valuable guidelines to identify under which circumstances each scheduling scheme should be utilized. The comparative analysis has considered the traffic models recommended by 3GPP evaluation guidelines and, for the first time, it has quantified the impact of different PDB requirements on the performance of NR-V2X Mode 2. The obtained results revealed that different PDB

Table 6
SPS Scheme, Mixed Traffic Scenario - LRR, SRR, and URR.

	LRR		SRR		URR	
	PDB = RRI	PDB = 10 ms	PDB = RRI	PDB = 10 ms	PDB = RRI	PDB = 10 ms
$\Delta = 10\%$	0	0.69	0.06	0.28	0.41	0.53
$\Delta = 25\%$	0	0.58	0.05	0.24	0.35	0.44
$\Delta = 50\%$	0	0.39	0.03	0.16	0.23	0.29
$\Delta = 75\%$	0	0.19	0.02	0.08	0.12	0.15

requirements do not affect the DS scheme operation, whereas they can significantly deteriorate the SPS performance when fixed or variable size aperiodic traffic is considered.

Simulation results demonstrated that the SPS scheme represents the best scheduling scheme for serving fixed size periodic traffic. In the (fixed or variable size) aperiodic traffic case, the DS scheme achieves the best performance, especially with more stringent PDB requirements. Our study has also shown that adapting the scheduling scheme to the type of generated traffic guarantees the best performance in mixed traffic scenarios, i.e., where fixed size periodic traffic and variable size aperiodic traffic sources coexist within the same NR-V2X system.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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