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Full duplex based collision detection to enhance the V2X sidelink autonomous mode

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ABSTRACT

The Third Generation Partnership Project (3GPP) recently introduced the fifth-generation (5G) new radio (NR) sidelink to enable vehicle-to-everything (V2X) communications supporting advanced safety services. Nevertheless, improvements over the previous generation still pose challenges to meet the reliability and latency requirements of V2X communications, particularly in the allocation of distributed resources, i.e., Mode 2. In Mode 2, vehicles autonomously select radio resources for their message transmissions and can maintain the selected resources for a given reservation period to efficiently handle periodic data traffic. However, potential collisions during this period may remain undetected due to half-duplex communications and unacknowledged broadcast transmissions, resulting in persistent message losses and posing a threat to road safety. This paper aims to improve the 5G NR-V2X sidelink for systems beyond 5G-Advanced by exploiting full-duplex transceivers. We propose a novel medium access control (MAC) scheme where vehicles can detect collisions while transmitting, dynamically adapt the collision detection threshold according to the measured channel load, and react to detected collisions through appropriate resource reselection and retransmission procedures. Extensive simulations conducted under various settings show that this MAC scheme brings substantial performance gains in terms of reliability and latency, compared to the current legacy Mode 2 procedure and a benchmark full-duplex scheme from the literature.

1. Introduction

The Third Generation Partnership Project (3GPP) has specified, since Release 12, the so-called PC5 interface for direct communications between devices on the *sidelink*. In subsequent releases, these specifications evolved by addressing vehicle-to-everything (V2X) communications for the long-term evolution-V2X (LTE-V2X) sidelink in Release 14, and the fifth generation (5G) new radio-V2X (NR-V2X) sidelink in Release 16. The 5G NR-V2X communication technology is expected to play a pivotal role in enabling, through the V2X sidelink interface, the timely dissemination of vehicles' and surrounding status information, as well as planned trajectories and maneuvers, to enable connected and automated driving. For most of these V2X applications, all vehicles must exchange information with all their neighbors; therefore, all-to-all broadcast transmissions are expected to represent the predominant traffic type.

Starting from Release 14, the allocation of sidelink radio resources to communicating vehicles can be either controlled by the network or decided autonomously by the vehicles themselves; respectively, the two allocation modes are called Mode 1 and Mode 2 in Release 16. Mode 2 (a.k.a. autonomous mode) can operate without infrastructure support and, therefore, even when not in network coverage; for this reason, it is expected to be the most deployed mode in practice on a large scale. In the autonomous mode, the sidelink radio resources are selected in a distributed manner by vehicles based on the sensing of the past status of the channel. To efficiently serve periodic data traffic, the selected resources may be maintained for several messages, according to a procedure called sensing-based semi-persistent scheduling (SB-SPS). However, imperfections in the channel sensing due to hidden terminals, vehicle mobility and the usage of onboard half-duplex (HD) transceivers may expose exchanged messages to interference and

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collisions. With SB-SPS, the repeated use of the same resources may result in several consecutive collisions, posing a threat to road safety. This phenomenon is commonly referred to as *persistent collisions* in the literature.

The 3GPP specifications in Releases 16 and 17, in addition to the 5G NR enhancements like flexible numerology, added new features to improve the reliability of the sidelink [1]. These new features include multiple blind retransmissions and the support for unicast and groupcast with a feedback channel to return an acknowledgment. Another added feature is the inter-user equipment coordination (IUC), which allows one vehicle to share its view of the channel occupation with other users; however, this feature is limited to unicast and groupcast. Despite the several innovations, the issue of persistent collisions with periodic broadcast traffic remains present.

The second phase of standardization of 5G has now started in Release 18 and will continue towards the sixth generation (6G), maintaining V2X as one of the vertical applications of major interest. Among the key technologies for 6G, a promising one is in-band full-duplex (FD), i.e., the ability to transmit and receive simultaneously in the same band [2,3]. FD has already been introduced in Release 17 for the specific case of integrated access and backhaul (IAB), with prospects for extension to the access network in future standardization efforts, encompassing both the downlink/uplink and the sidelink interfaces [4]. Moreover, although FD is more than a decade old, the interest in this technology has recently revived, thanks to the maturity of self-interference (SI) cancellation techniques [3,5], which make FD practically deployable. Notably, the FD technology deployment is considered more viable on board the vehicles, where the energy, computing and space constraints related to the complexity of FD transceivers are relaxed compared to small-form-factor consumer devices [6].

Some researchers started considering FD communications to enhance sidelink when operating in the autonomous mode [7–10]. The underlying idea in these works is to use the capability of FD transceivers of "listening while talking" to improve the channel sensing procedure by detecting incumbent collisions with transmitting messages. These studies provide only early results on the potential of FD applied for the sake of collision detection and all present some limitations (further detailed in Section 2).

The work presented here significantly extends our previous investigation in [10], both in terms of proposal and evaluation settings, metrics and results. More specifically, it proposes a comprehensive medium access control (MAC) scheme called *CD3R*, which significantly advances the state of the art in the following aspects:

- This scheme enhances the legacy Mode 2 SB-SPS by integrating FD transceivers capable of detecting collisions during transmission. Upon collision detection, the FD transceiver reacts by employing various proposed variants within the scheme by: *(i)* changing the periodically reserved resource to promptly interrupt potential persistent message losses, and/or *(ii)* dynamically triggering message retransmissions. In particular, four novel additional schemes are foreseen compared to the one originally conceived in [10]. This dynamic approach enhances message reliability without the need to reserve additional resources for blind retransmissions of each packet;
- The occurrence of a collision is detected by comparing the received power level with a given collision detection threshold. The threshold is adaptively set based on channel measurements that are already executed by the vehicle for congestion control purposes, as specified in [11]. A fixed threshold was instead considered in our previous work in [10] as well as in other works in the literature;
- The proposed scheme is assessed through extensive simulations assuming broadcast communications under a wide variety of settings (e.g., different SI cancellation capabilities, collision detection thresholds, vehicle densities, number of retransmissions, packet size, channel bandwidth) when considering the last available 3GPP sidelink specifications in Releases 16 and 17. Its performance is compared against the legacy 5G NR-V2X Mode 2 and another benchmark from the literature.

The remainder of the paper is organized as follows. Section 2 provides background and motivations for our work by presenting an overview of 5G NR-V2X sidelink specifications and Mode 2 operation, and by summarizing the related literature on FD for V2X sidelink. The new CD3R framework is then discussed in Section 3. Simulation settings are reported in Section 4, and this is followed by a discussion of the achieved results in Section 5. Finally, Section 6 summarizes the main findings and provides potential directions for future work.

2. Background and motivations

2.1. The 5G NR-V2X autonomous mode

The NR-V2X sidelink is designed to support advanced V2X services through flexible physical (PHY) and MAC layers. Its main features are hereafter recalled; more details can be found in [1,12].

PHY layer. The NR-based PHY layer uses orthogonal frequency-division multiplexing (OFDM) with flexible numerology and variable subcarrier spacing (SCS) within two frequency ranges, one below 6 GHz (FR1), expected in practice in the intelligent transport system (ITS) band at 5.9 GHz, and the other one at millimiter wave (mmWave) band (FR2). The slot duration in the time domain depends on the numerology; it is 1, 0.5, or 0.25 ms for SCS of 15, 30, or 60 kHz, respectively. A *subchannel* in the frequency domain is a predefined number of groups of 12 subcarriers called physical resource blocks (PRBs). Based on the modulation and coding scheme (MCS) and the payload size, one or more subchannels can be used to transmit a message in the same slot.

MAC layer. Mode 2 is based on a sensing procedure, where each VUE senses the channel before transmitting, identifies the available resources (i.e., set of contiguous subchannels expected to be not accessed by surrounding VUEs), and performs a resource selection that tries to minimize the risk of collisions. In particular, a VUE continuously monitors the sidelink radio resources status by *(i)* measuring the reference signal received power (RSRP) in each subchannel and *(ii)* decoding the sidelink control information (SCI) associated with each data message, which indicates the resources reserved for upcoming transmissions. The resources assumed available are those which are not indicated by any received SCI or with an associated RSRP below a given threshold (hereafter called RSRP sensing threshold). Moreover, the available resources are always considered within a time window determined by the maximum delay that can be accepted for the message (referred to as the delay budget). Finally, the VUE selects resources at random from the available ones for its data transmissions on the sidelink.

Once a resource is selected, the same subchannels can be reserved periodically for a certain duration. This resource scheduling is known as SB-SPS. SB-SPS was specifically designed to support applications generating periodic broadcast messages as opposed to the sensing-based dynamic scheduling (SB-DS), where new resources are selected per each new packet. SB-SPS has been proved to significantly outperform SB-DS in the presence of periodic traffic [13]. In SB-SPS, the periodicity, called resource reservation interval (RRI), can be any multiple of 100 ms up to 1 s, or any integer number of milliseconds between 1 and 99 ms from a preconfigured list specified by the network. The reservation duration is regulated by using a counter called reselection counter (RC), which is randomly set to a number, hereafter n_{SPS}, that depends on the RRI. For example, n_{SPS} is uniformly distributed between 5 and 15 if the RRI is 100 ms. The RC is decreased at each RRI until it reaches 0. Then, probabilistically either a new resource is selected (reselection), or the same one is maintained, and the RC is again randomly initialized.

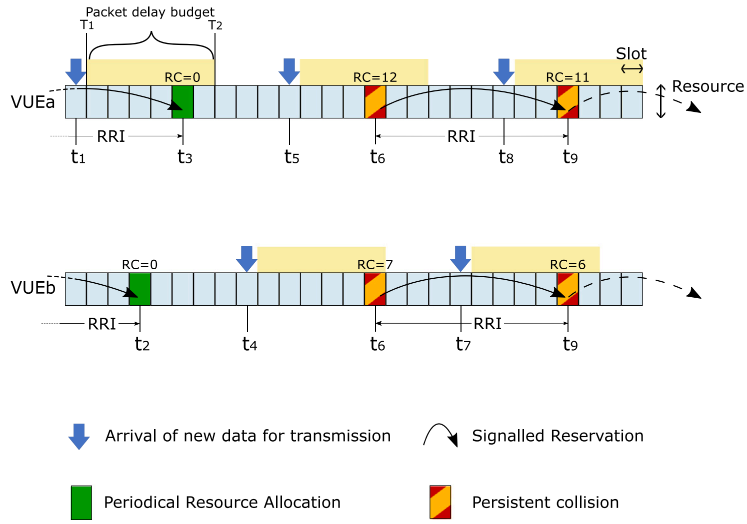


Fig. 1. Legacy SB-SPS. $\mathrm{VUE_a}$ and $\mathrm{VUE_b}$ perform a reselection at time t_5 and t_4, respectively, due to RC = 0. The two VUEs select the same resource and experience a collision at time t_6. Since the allocation is performed with the same periodicity, the collision repeats at time t_9 and will repeat again at least until the RC of either VUE reaches 0.

The decision is based on a parameter called keep probability, hereafter denoted as p_k, which is set by the network between 0 and 0.8. Smaller p_k implies more frequent reselections and, hence, breaking potential recurrent collisions more quickly, whereas larger p_k allows for more stable allocations and, therefore, better sensing procedures.

VUEs must also perform the resource re-evaluation procedure, introduced in NR-V2X. Shortly before transmitting in a selected resource, the VUE checks if the resources for the imminent transmission are still available or if they have been reserved by late-arriving SCIs from neighboring VUEs. If after the re-evaluation, the selected resources would not be part of the set of available resources, new resources must be selected. The resource re-evaluation is mandatory for all transmissions occurring on selected resources, which are resources not previously reserved and advertised by an SCI, i.e., the first transmission after a resource reselection [14].

Blind retransmissions. In NR-V2X, the same message can be replicated more times in the so-called blind retransmissions. The selection of the resources for the retransmissions goes through the same process, with an additional constraint to have no more than 31 slots of delay between consecutive replicas. Additionally, for the groupcast and unicast cases, a feedback channel is also available, which may be used to provide acknowledgments and request retransmissions.

Congestion control. Given the life-critical applications to be supported, rules are defined on a regional basis, e.g., in Europe by ETSI [11], to avoid excessive channel load and thus, keep control of the number of collisions. These procedures impose that each VUE continuously monitors the channel status and captures it in what is normally called channel busy ratio (CBR) [15]. The CBR, which indicates the fraction of used channel resources in a given observation interval, is then used by the VUE to adapt its transmission parameters (e.g., maximum resource allocation periodicity, maximum signal power).

Studies on Mode 2. The sidelink autonomous mode has been thoroughly investigated in the literature, with several enhancements proposed to the legacy SB-SPS procedure, e.g., [16–18]. The interested reader can also find studies discussing the impact of relevant parameters (e.g., numerology, retransmissions, RRI, keep probability) of 5G NR-V2X in [17,19–23]. Here, we aim at improving the performance by exploiting FD for collision detection.

2.2. The issue of undetectable collisions in Mode 2 SB-SPS

Despite the improvements of Releases 16 and 17, Mode 2 still suffers from non-perfect vehicle coordination and not fully reliable channel sensing due to hidden terminals, vehicle mobility, channel impairments, some randomness elements in the resource selection, and HD limitations. The primary concern is that an incorrect choice of the sidelink resources in the SB-SPS can produce persistent collisions due to the periodic resource reservation mechanism, with consequent loss of awareness information from neighboring vehicles and, therefore, a detrimental impact on road safety. For example, in Fig. 1, two VUEs select the same resources, and their transmissions repeatedly collide until the reservation period ends for either one of them, and a different resource is selected.

It must be noted that the previously mentioned resource re-evaluation mechanism, introduced in Release 16, cannot prevent this type of collision, as the re-evaluation cannot discover that multiple users are selecting the same resource for their initial transmissions. For example, again in Fig. 1, the re-evaluation performed by $\mathrm{VUE_a}$ before transmitting at time t_6 cannot detect the intention of $\mathrm{VUE_b}$ to use the same resource [24].

To offer vehicles the capability of detecting and coping with collisions due to hidden terminals, Release 17 added the already mentioned IUC [14]. Specifically, IUC refers to the possibility that an assisting VUE ($\mathrm{VUE_A}$) gives another VUE ($\mathrm{VUE_B}$) information about the set of resources to be used or to be excluded by $\mathrm{VUE_B}$. In this way, $\mathrm{VUE_A}$, which is aware of another transmitting VUE ($\mathrm{VUE_C}$) hidden from $\mathrm{VUE_B}$, can help $\mathrm{VUE_B}$ become aware of such transmission and avoid using the same (colliding) resources as $\mathrm{VUE_C}$. Although IUC may reduce the probability of collisions, it does not resolve those that have already occurred and cannot break persistent collisions. Moreover, the coordination requires additional signaling sent on the sidelink between the VUEs and is currently restricted to the unicast and groupcast cases. Extending this concept to the broadcast case is not straightforward and requires further investigations. Indeed, in the broadcast case, if all receivers assist the transmitting VUE, by sharing the report including their non preferred resources, the overhead would be huge. Workarounds are needed to properly select the VUE which needs to provide assistance, as preliminarily studied in [25].

Our work aims to overhaul Mode 2 operation, by relying on the FD capability of VUEs to identify and resolve otherwise undetected collisions, without increasing the signaling overhead. The proposed solution is applicable to broadcast transmissions and, under this perspective, can be considered as complementary to IUC.

2.3. Full duplex in V2X scenarios

FD refers to the capability of a radio transceiver to transmit and receive in the same band simultaneously [5,26]. The benefit of such a technique is limited by the large SI that is unavoidably generated when the transmitted signal couples back to the receiver in the FD transceiver. The cost and complexity of self-interference cancellation (SIC) techniques have hindered the practical implementation of FD transceivers in consumer devices in the past years. However, considerable progress in SI suppression has been made recently, using multi-stage receiver architectures based on RF passive isolation techniques combined with active analog and digital cancellation techniques. Such sophisticated SIC schemes can typically achieve 85–110 dB of SIC, which is sufficient to bring SI down to the noise floor in short-range communications systems, where the transmit power remains limited. Vehicles are the best candidates to host FD UE transceivers since issues related to cost, miniaturization and increased computational complexity are largely mitigated [6].

A number of studies have considered the application of FD in vehicular environments by focusing on the capability of sensing the medium while transmitting. This proved to be greatly beneficial for (unacknowledged) broadcast traffic for which packet losses may detrimentally affect the safety of vehicles. The first attempts refer to the broadcasting performance of the IEEE 802.11-based technology for V2X communications [27,28].

A few works subsequently focused on FD applied to the cellular V2X sidelink. The proposal in [7] exploits FD transceivers on board the VUE to dynamically set the keep probability p_k in the SB-SPS upon detecting a collision while transmitting. In particular, for a given VUE, the keep probability is set to a lower value (meaning a higher probability to change resources after a reservation period) when more collisions are detected while transmitting. The works in [8,9] both propose to react to a detected collision. In the solution in [8], the detecting VUE keeps the same subchannels and retransmits in the first available slots according to the past sensing procedure. Up to 3 re-attempts can be performed according to the priority of the message to be transmitted. The drawback of this approach is that the detected collision is bound to occur again if the priority is the same since the contending stations use the same resources for the retransmission. In [9], a transmission is immediately aborted if a collision is detected, and the VUE goes to the reservation stage to identify new resources. Results appear promising, even if the feasibility and effect of sudden abortion are not discussed in detail.

Besides the aforecited weaknesses, all the works mentioned above neglect, among other features, the presence of blind retransmissions. Moreover, neither of these studies investigated the impact of the collision detection threshold, which defines the power level for the received signal to assume a collision is occurring. Indeed, its setting may significantly affect the performance: on the one hand, a too low value would trigger frequent detection of collisions, with counterproductive instability of the SB-SPS process due to frequent changes in the occupied resources; on the other hand, a too high value would simply disable the capability of detection and bring the system to the legacy behavior.

Only in our previous work in [10], preliminary considerations on this effect were provided. There, FD was exploited by VUEs operating over NR-V2X in Mode 2 to enforce both simultaneous data transmission and reception and simultaneous data transmission and channel sensing with collision detection capability. The achieved simulation results showed that adding the FD capability to the legacy SB-SPS to allow simultaneous data transmission and reception has a marginal impact, as also theoretically argued in [29] (in that case focusing on LTE-V2X sidelink). Differently, when collision detection (CD) is used to enforce resource reselection, it can break persistent losses over a reserved resource and significantly improve the reliability of periodic packet transmissions.

2.4. Paper contribution

In this paper, we aim to go beyond the above-summarized literature by proposing an extension of Mode 2 SB-SPS that, by exploiting FD transceivers onboard of VUEs, can detect (otherwise undetected) collided messages and trigger message retransmissions and resource reselection. Message retransmission is performed to counteract the loss of the collided packet and to increase the robustness and reliability of Mode 2. Differently, the resource reselection reacts to a collision by breaking possibly persistent losses due to the periodical resource reservation mechanism of SB-SPS.

As mentioned above, this work builds upon our previous investigation in [10], but it significantly advances the precedent analysis by the following aspects:

- It is extended to the case of blind retransmissions (not considered in [10] and other previous works);
- It allows to react to a detected packet collision *not only by selecting a different resource for the subsequent packet transmission* as in [10], but also *by immediately retransmitting the same packet*. This design choice improves the effectiveness of retransmission by dynamically triggering them to enhance message reliability when they are more likely needed (i.e., when a collision is detected). Continuously reserving resources for blind retransmissions as foreseen by the legacy protocol may, in fact, increase the collision probability and eventually reduce the performance, as proven for example in [19];
- It implements a *dynamic and practical setting* (instead of a static one as in [10]) *of the power threshold* that is used by the VUE to determine if a collision is occurring. In particular, the power threshold is set, after a comprehensive tuning simulation campaign, according to the perceived channel occupation status.

The main strengths of the proposed scheme can be summarized as follows:

- It builds upon the legacy SB-SPS, exploiting its consolidated procedures for resource selection and continuous reservation;
- It addresses the issue of persistent collisions severely affecting broadcast communications;
- It does not require additional signaling;
- It is fully in line and even complementary with some efforts in Releases 16 and 17 to increase the sidelink reliability by coping with undetectable collisions, such as the IUC, which mainly targets unicast and groupcast communications;
- It leverages measurements of the average received power that are simple to obtain after SI cancellation and estimations of the channel occupation that are already available for congestion control purposes in legacy devices.

3. The collision detection-driven resource reselection and retransmission (CD3R) MAC scheme

The proposed scheme, which includes five alternative configurations, is summarized in Fig. 2. The process starts when a new packet needs to be transmitted in a resource already selected by the SB-SPS protocol. While the transmission is being performed, the collision detection is carried out as detailed in Sections 3.1 and 3.2. If a collision is not detected, then the process proceeds with the legacy SB-SPS. Otherwise, the VUE applies either or both of the following two actions, depending on the configuration:

- *Immediate resource reselection (RR)*: the detected collision triggers a resource allocation change for the next message transmission. If blind retransmission was used, collision detection is possible on both the original packet and its repetition; two variants (*Immediate RR, Single CD* and *Immediate RR, Double CD*) are considered in this case, depending on how many collisions (one or two) must be detected to trigger a change in the resources;
- *CD-driven retransmission:* a message retransmission is triggered.

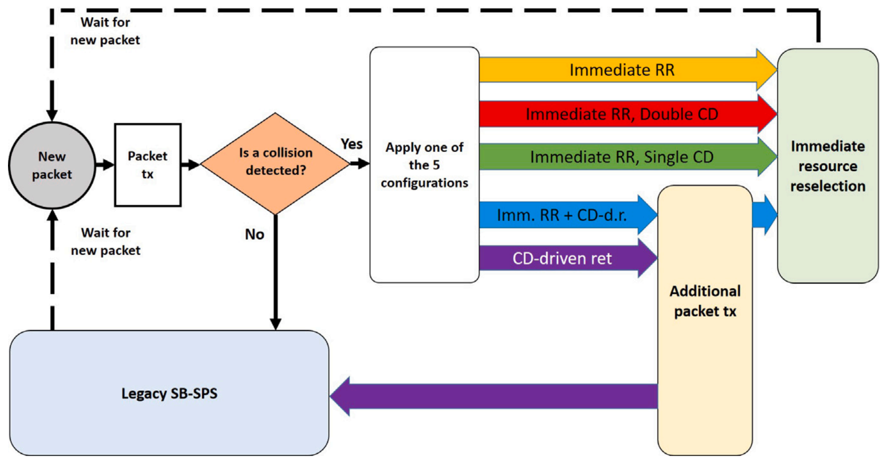


Fig. 2. Overview of the CD3R MAC scheme with the possible alternative configurations. The colors of the arrows are consistent with the colors used in numerical results in Section 5. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The use of either or both of these actions depends on the setting of six parameters N, Ω, ω, φ, θ, and η, whose definitions and possible values are explained in Table 1. The five configurations are described in details from Sections 3.3 to 3.5, and a summary is eventually provided in Section 3.6.

3.1. Collision detection

An FD-enabled VUE senses the channel while transmitting and detects the possible occurrence of a collision. To this aim, the FD transceiver performs SIC to reduce the power contribution due to the ongoing transmission, i.e., the self-interference. In practice, this operation typically entails a first step with passive SI attenuation, which suppresses part of the SI before it enters the receiver radio frequency (RF) chain circuit, e.g., through antenna isolation. As a second step, active SIC is applied in the analog and/or digital domain to cancel any residual SI by subtracting an estimated SI signal [30,31].

The received power at VUE i, while VUE i is transmitting, is represented on the left and right side of Fig. 3 before and after SI cancellation, respectively.

The residual power P_{res_i} after SI cancellation can be written as:

$$P_{\text{res}_i} = P_{\text{N}} + P_{\text{RSI}_i} + P_{\text{INT}_i}, \tag{1}$$

where:

- P_{N} is the additive white Gaussian noise power;
- P_{RSI_i} represents the residual SI, defined as:

  $$P_{\text{RSI}_i} \triangleq K_{\text{SI}i} P_{\text{tx}_i}, \tag{2}$$

  i.e., the power transmitted by VUE i itself, P_{tx_i}, attenuated by the SIC factor $K_{\text{SI}i}$; note that, since P_{tx_i} and $K_{\text{SI}i}$ are known at the transmitter, also P_{RSI_i} is known;
- P_{INT_i} accounts for the interference power received from other VUEs simultaneously transmitting, defined as:

  $$P_{\text{INT}_i} \triangleq \sum_{k\in\mathcal{V}_{S_i}} \eta_{ki} P_{\text{rx}_{ki}}, \tag{3}$$

  where $\mathcal{V}_{S_i}$ is the set of VUEs transmitting in the same slot used by VUE i, $P_{\text{rx}_{ki}}$ is the power received at i from the interferer k, and η_{ki} is a coefficient that quantifies how much power is sent by VUE k in the subchannels used by VUE i, related to the transmission power of VUE k. η_{ki} is equal to 1 if VUE k and i use the same subchannels; otherwise, it is lower than 1 and accounts for possible partial overlapping and in-band emission (IBE) [32].

Table 1
Definitions and possible values of the main parameters of the CD3R MAC scheme.

Parameter	Description
N	Transmission being performed (1 for the initial transmission, 2 for the first retransmission, etc.)
Ω	Number of reserved retransmissions (0 if no retransmissions)
ω	Boolean value equal to 1 if CD-driven retransmission is enabled, 0 otherwise
φ	Boolean value equal to 1 if all transmission attempts need to experience a collision to trigger resource reselection, 0 otherwise
θ	Boolean value equal to 1 if immediate reselection is enabled, 0 otherwise
η	Number of collisions detected
P_{d}	Power threshold above which an occurring collision is assumed

It can be noted that the residual power inherently captures in an aggregate manner the number of interfering vehicles and characteristics such as the distances between them and the transmit power. For instance, the farther the interferers from the target vehicle i, the smaller such a contribution.

To determine whether a collision occurs or not, the residual power P_{res_i} is compared to a collision detection threshold $P_{\text{d}i}$, as shown in Fig. 3. Using an equation, a collision is detected if

$$P_{\text{res}_i} > P_{\text{d}i}\,, \tag{4}$$

where (see Fig. 3)

$$P_{\text{d}i} \geq P_{\text{RSI}_i}\,. \tag{5}$$

3.2. Adaptive collision detection threshold based on the CBR

The setting of the parameter P_{d} clearly affects the effectiveness of the collision detection, as shown in [10]: a too low value may in fact cause too frequent collision detections and consequently too frequent resource reselections, whereas a too high value may cause collisions to be rarely detected and thus, reduce the effectiveness of the protocol. In this work, we propose to dynamically set P_{d} as a function of the CBR, which measures the average perceived channel occupation and is normally already calculated for congestion control purposes.

According to [11], the CBR is computed as:

$$CBR = \frac{N_{\text{busy}}}{N_{\text{CBR}}}, \tag{6}$$

where N_{busy} represents the number of subchannels sensed as busy during an observation window of duration T_{CBR}, set to 100 ms, and

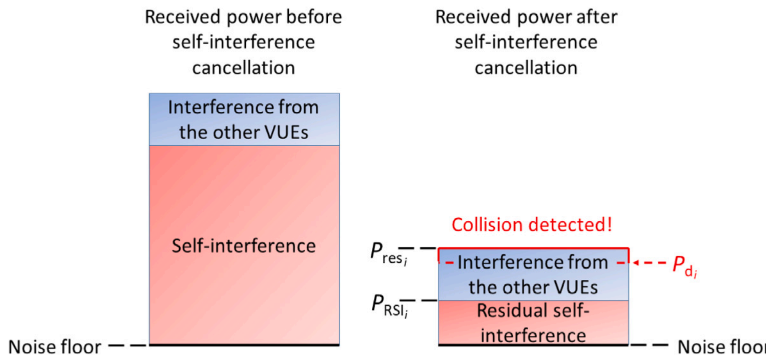


Fig. 3. Representation of the power levels before (left) and after (right) self-interference cancellation and indication of the collision detection threshold.

N_{CBR} is the overall number of subchannels available during the T_{CBR}-long observation window. A subchannel is considered busy when the received power in that subchannel is above a pre-configured threshold, set to −94 dBm [11].

Given the measured CBR, the threshold is obtained based on the equation

$$P_{\mathrm{d}} = f_{\mathrm{d}}(CBR), \tag{7}$$

where f_{d} is a function to be optimized. In Section 5.1, such a function is derived based on extensive simulations.

3.3. Immediate RR without retransmissions

If a collision is detected during a transmission, one option is to trigger the resource reselection so the subsequent message will not persist in using an interfered resource. This procedure, derived from [10], is called *Immediate RR*. Practically, this means that the RC, used by the SB-SPS to determine how long the same subchannels are periodically reserved, is immediately reduced to zero. Consequently, when a new packet is generated after the collision, irrespective of the previous reservation, new resources are selected, regardless of the value of the keep probability p_{k}, and the reservation counter is restarted following the SB-SPS rules.

The process is exemplified in Fig. 4, where two VUEs, referred to as $\mathrm{VUE}_{\mathrm{a}}$ and $\mathrm{VUE}_{\mathrm{b}}$, detect a collision at instant t_6. Consequently, in t_6, they both reduce the RC to zero and prepare for a resource reselection. Then, as soon as they generate a new packet (t_8 and t_7, respectively), they reset the RC to a new value, and they both reselect a new resource (in t_{10} and t_8, respectively). The resource corresponding to the previous periodical reservation indicated by the collided packets is eventually unused (time instant t_9). In addition, by acting directly on the setting of the RC, the proposal does not need to track additional parameters. It is important to note that neighbors are not advised of the resource reselection. Such a design choice allows no modifications in the signaling procedures. Therefore, it is fully compatible with legacy devices.

3.4. Immediate RR with blind retransmissions

So far, we have investigated the performance of the Immediate RR solution, assuming that each packet is transmitted once, without retransmissions (i.e., $\Omega = 0$). However, NR-V2X also foresees multiple blind retransmissions of the same packet[1] to improve the reliability of messages exchanged in broadcast.

In the presence of retransmissions, thanks to an FD-enabled transceiver, a VUE can sense the channel both during the transmission and the retransmission and apply CD to determine if resource reselections are necessary. Different behaviors, captured by the boolean parameter φ, may be considered according to how the transmitting VUE reacts to the detected collisions.

Assuming a single retransmission ($\Omega = 1$), this section describes the possible modifications to the proposed Immediate RR configuration when retransmissions are enforced.

3.4.1. Double collision-driven immediate RR

The first configuration, which we refer to as *Immediate RR, Double CD* and indicate this through the parameter φ set to 1, foresees that a transmitting VUE triggers the resource reselection only if *both the transmission and retransmission are detected to experience a collision* (see Fig. 5(a)). On the other hand, if only one (or zero) collision is detected, the VUE keeps the selected resources unless differently driven by the SB-SPS procedure. The rationale behind such an approach is that if only one of the two transmissions is compromised and the other can be considered successfully received, the overall transmission attempt can still be assumed successful.

When a collision is detected for both transmissions, both the corresponding resources are changed. The selection of new resources when a double collision is detected provides different benefits. First, changing the resources makes the collision less likely to persist. Second, by resolving conflicts, the neighboring VUEs will receive the transmission with a higher signal-to-interference-plus-noise ratio (SINR).

Similarly to the Immediate RR configuration, applied when retransmissions are not considered, the previously selected resources are left unused by the VUE that detected the collision.

3.4.2. Single collision-driven immediate RR

An approach with more frequent reselections and potentially even less persistent collisions is to let a VUE trigger a resource reselection when a collision is detected in *at least one of the two resources used for the transmission and retransmission*. We refer to this configuration as *Immediate RR, Single CD* and indicate it by setting the parameter φ to 0 (see Fig. 5(b)). In particular, only the resource where the collision is detected is reselected at the arrival of a new message.

The resource reselection triggered upon detecting a collision on either the first transmission attempt or retransmission makes both transmission attempts more reliable. Ultimately, when a collision is perceived on both resources, the configuration falls back to the double collision-driven resource reselection, and both resources are changed.

Fig. 5(b) depicts different possible situations to clarify the described procedure and the consequence of a collision detection. The collision can occur on the first resource (cases 3 and 4) or the second resource (cases 1 and 2). The new resource might be selected after the one kept (cases 1 and 3) or before it (cases 2 and 4). In all cases, one resource is reserved but not eventually used due to the reselection.

[1] The retransmissions of broadcast packets are called blind as they are not based on a feedback. Sometimes they are also referred as repetitions.

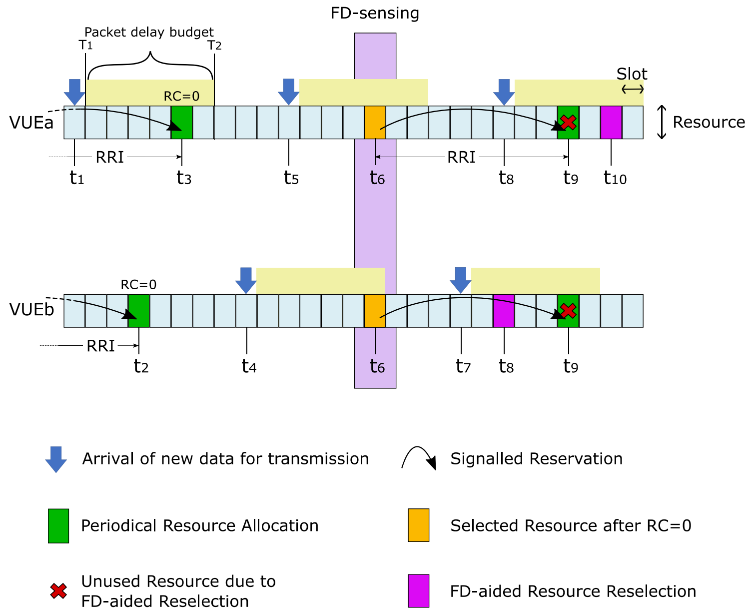


Fig. 4. Immediate RR. VUE_a and VUE_b experience a collision at time t_6. Regardless of the value of the RC counter, as soon as they generate a new packet (t_8 and t_7, respectively) they reset the RC counter and they both reselect a new resource (in t_{10} and t_8, respectively). The previously selected one, at time instant t_9, is unused.

3.5. CD-driven retransmissions w/o immediate RR

The Immediate RR solution does not modify the Mode 2 resource allocation procedure. Blind retransmissions, if enabled and advertised by the sending VUE, are enforced regardless of the outcome of the CD procedure. Notwithstanding, blind retransmissions foreseen by Mode 2 may not be beneficial under congested traffic conditions, as also proven in [19]; judicious enforcement of retransmissions should be devised instead.

In this work, we leverage the CD mechanism also to dynamically trigger a retransmission if collisions are detected during the regular transmissions, as shown in Fig. 6(a). This feature, called *CD-driven retransmissions* and indicated by setting the parameter ω of CD3R to 1 (otherwise ω is set to 0), is intended to provide a new chance to correctly deliver a packet that had presumably collided.

In particular, the VUE detecting a collision randomly selects the resource for the retransmission in the subsequent window of 31 slots,[2] indicated as T_1-T_{ret} in Fig. 6(a), but in any case within the packet delay budget of the first transmission, i.e., within T_2. Differently from the previous case (Fig. 5), the resource selected for the retransmission is not advertised during the first transmission, as the retransmission is triggered after the collision has already occurred.

The CD-driven retransmissions feature can be combined with the Immediate RR, as shown in Fig. 6(b), to further benefit of the resource reselection for subsequent packet transmissions.

3.6. Scheme summary and possible configurations

A summary flowchart of the proposed MAC scheme, CD3R, is shown in Fig. 7. Depending on the settings of the parameters listed in Table 1, the different configurations of CD3R are possible, as detailed in Table 2.

In particular, when a new packet is generated (left side of Fig. 7), N is initialized to 1 and η to 0. Then, during the transmission the device measures the received power and compares it with the collision detection threshold obtained as a function of the current CBR. If a collision is not detected, the legacy SB-SPS procedure is followed. Otherwise, η is increased by one. If φ is set to 1 and η is not larger than Ω, it means that the number of detected collisions is not yet sufficient to trigger a reselection or a retransmission and the legacy SB-SPS procedure continues. Otherwise, first the remaining retransmissions are performed, second a CD-driven retransmission is commanded if ω is set to 1 and the delay budget allows it, and finally an immediate resource reselection is performed if θ is equal to 1. If θ is set to 0, the legacy SB-SPS resource allocation procedure is used at the end of the process.

Table 2
CD3R configurations and parameters setting (n.r. when not relevant).

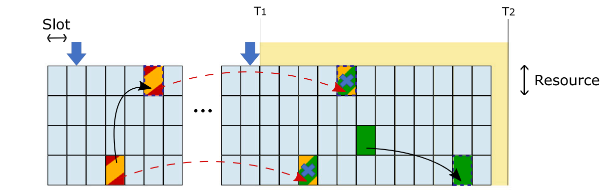
Configuration	Settings
Immediate RR	$\Omega = 0$, $\varphi =$ n.r, $\omega = 0$, $\theta = 1$
Immediate RR, Double CD	$\Omega = 1$, $\varphi = 1$, $\omega = 0$, $\theta = 1$
Immediate RR, Single CD	$\Omega = 1$, $\varphi = 0$, $\omega = 0$, $\theta = 1$
CD-driven retransmissions	$\Omega = 0$, $\varphi =$ n.r., $\omega = 1$, $\theta = 0$
Immediate RR + CD-driven retransmissions	$\Omega = 0$, $\varphi =$ n.r., $\omega = 1$, $\theta = 1$

4. Simulation settings and modeling

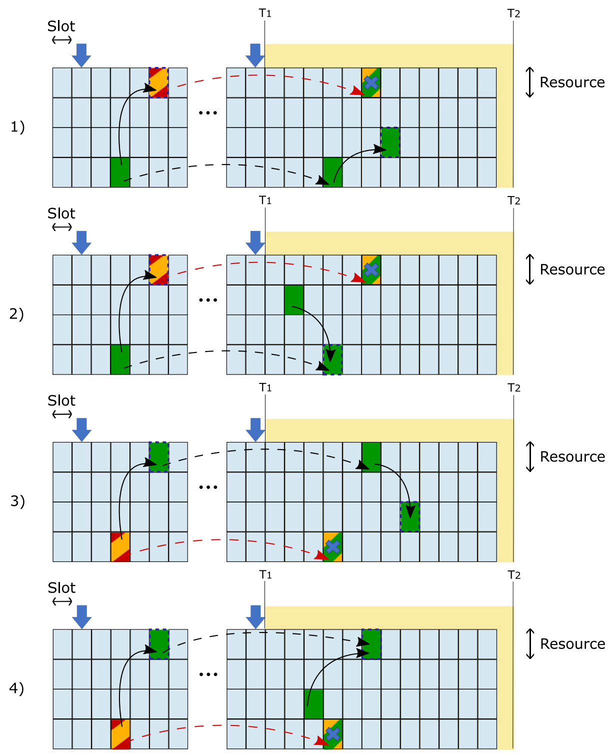
Large-scale simulations have been conducted to assess the performance of the conceived solution. Simulation is among the most common methodologies in the literature investigating the performance of NR-V2X sidelink, see e.g., [13,20,24], and its enhancements [16–18]. In particular, the assessment campaigns have been conducted using WiLabV2Xsim [19], an open-source simulator developed in MATLAB that allows studying the delivery performance of messages exchanged over NR-V2X sidelink, with a focus on the PHY and MAC layer behavior.[3] The simulator accounts for the latest 3GPP specifications in Releases 16 and 17 and has been specifically overhauled to encompass the devised FD-enhanced resource reselection and retransmission mechanisms.

[2] Without loss of generality, we consider 31 slots as for blind retransmissions foreseen in the legacy SB-SPS scheme. However, simulations conducted without this constraint provided similar results.

[3] The simulator is available at https://github.com/V2Xgithub/WiLabV2Xsim.



(a) Immediate RR, Double CD.



(b) Immediate RR, Single CD.

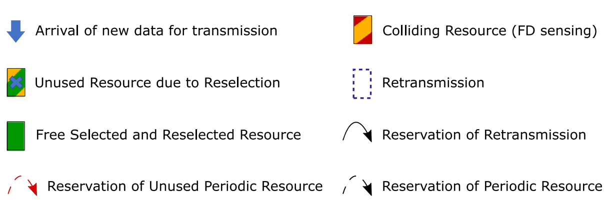


Fig. 5. Immediate RR in the presence of retransmissions. VUEs reselect the resources when they experience collisions on both transmission and retransmission (a) and on either the transmission or the retransmission (b,1–4).

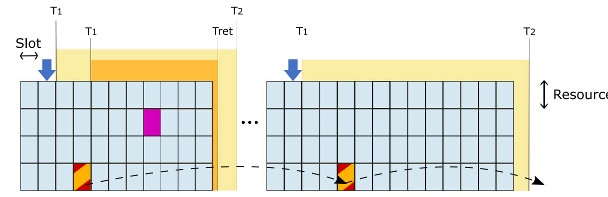
4.1. Abstraction of the physical layer

When simulating large wireless networks, it is necessary to abstract the PHY layer with a good trade-off between accuracy and complexity. In the adopted simulator, the abstraction is based on the calculation of the average SINR per each transmission and each possible receiver, as hereafter summarized and detailed in [33]. This approach is very similar to what done in most of the related work, among which we can mention as examples [20] or [24].

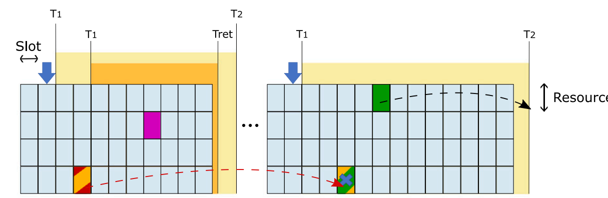
First of all, per each transmitting station i and each possible receiving station j, the average received power $P_{\mathrm{rx}_{i,j}}$ is calculated as:

$$P_{\mathrm{rx}_{ij}} = P_{\mathrm{tx}_i} G_i G_j A(d_{ij}) \theta_{ij}, \tag{8}$$

where P_{tx_i} is the transmitting power, G_i is the antenna gain at i, $A(d_{ij})$ is the average path-loss due to propagation, which is a function of the distance d_{ij} between i and j, and θ_{ij} is a log-normally spatially correlated random variable, assumed constant during the transmission. The latter variable models the large-scale fading, whereas the small-scale fading is averaged over the transmission and taken into account when the packet loss is evaluated.



(a) CD-driven retransmissions.



(b) CD-driven retransmissions + Immediate RR.

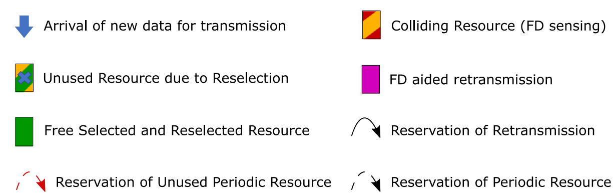


Fig. 6. CD-driven retransmissions when not coupled with Immediate RR (a) and when coupled with Immediate RR (b).

Then, per each transmitting station i, the average SINR Γ_{ij} at the generic receiving station j is calculated as:

$$\Gamma_{ij} = \frac{P_{\mathrm{rx}_{ij}}}{P_{\mathrm{N}} + \xi_j \eta_{ji} P_{\mathrm{RSI}_j} + \sum_{k \in \mathcal{V}_{\mathrm{T}/i,j}} \eta_{ki} P_{\mathrm{rx}_{kj}}}, \tag{9}$$

where, consistently with (1)–(3), P_{N} is the noise power, ξ_j is a binary variable indicating if station j is also transmitting in the same TTI, P_{RSI_j} is the residual self-interference (only relevant if $\xi_j = 1$, i.e., if station j is also transmitting in the same TTI), $\mathcal{V}_{\mathrm{T}/i,j}$ is the set of VUEs transmitting in the same TTI excluding i and j (if transmitting), and $P_{\mathrm{rx}_{kj}}$ is the power received at j from the interferer k. To consider that the interfering signal may not be using the same band used by the useful signal, η_{xi} is a coefficient that quantifies how much power is sent by VUE x in the subchannels used by VUE i, related to the transmission power of VUE x; η_{xi} is equal to 1 if VUE x uses the same subchannels as VUE i; otherwise, it is lower than 1 and accounts for possible partial overlapping and IBE; in the simulator, the IBE is calculated as the worst case allowed by the constrains imposed in [32, Clause 6.4.2.3] (including general, IQ image, and carrier leakage as detailed in Table 6.4.2.3-1). η_{xi} applies both to the self interference (if j is transmitting) and to the interference received from the other VUEs.

Once the average SINR is calculated, it is used to evaluate if the packet is successfully decoded or not. To this aim, a SINR vs. error rate curve is used that accounts for the small scale fading. The curve is approximated in this work as a threshold curve, given the limited accuracy loss shown in [33]. This means that, if Γ_{ij} calculated from (9) is larger than a given SINR threshold, then the packet is successfully decoded; otherwise, it is lost.

4.2. Settings

The main simulation settings are summarized in Table 3 and further detailed below. As a reference scenario we consider a highway with a

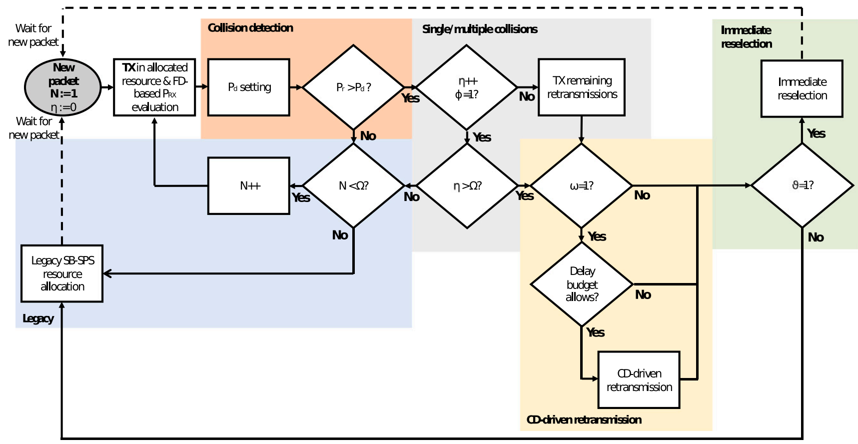


Fig. 7. Flowchart of the CD3R MAC scheme.

Table 3
Main simulation settings.

Scenario	
Road layout	Highway, 3+3 lanes
Density	Variable
Average speed	70 km/h
Power and propagation	
Channels	ITS bands at 5.9 GHz
Bandwidth	10 MHz[a]
Transmission power	23 dBm
Antenna gain (tx and rx)	3 dBi
Noise figure	9 dB
Propagation model	WINNER+, Scenario B1
Shadowing	Var. 3 dB, decorr. dist. 25 m
Data traffic	
Packet generation	Every 100 ms
Packet size	1000 bytes[a]
Radio access layer (NR-V2X)	
SI cancellation factor	−110 dB
Collision detection threshold, P_d	Automatic
MCS	11 (16-QAM, R_c = 0.3)
SINR threshold	9.95 dB
Subchannel size	10 PRB
Number of subchannels	5
SCS	15 kHz[a]
Keep probability	0.4
RSRP sensing threshold	−126 dBm
Min. time for the allocation, T_1	1 ms
Max. time for the allocation, T_2	100 ms

[a] Values used unless differently specified.

varying number of vehicles distributed across three lanes per direction. Each vehicle moves at a random speed defined according to a Gaussian distribution with a 70 km/h average [34] and a 7 km/h standard deviation.[4] Each VUE generates 1000 bytes-long packets every 100 ms. The packet size is in line with the estimations from the Car 2 Car Communications Consortium for Day-2 messages such as collective perception messages (CPMs) and maneuver coordination messages (MCMs) [35]. The same periodicity is also recommended by the 3GPP as *Periodic traffic Model 1* in TR 37.885 [34].

Transmissions occur within the 5.9 GHz band in a 10 MHz channel bandwidth, which is what currently adopted in most countries for ITS.

[4] Based on more simulations, not shown here for the sake of conciseness, it was observed that the results are similar when changing the average speed. The average speed mainly affects how long the vehicles remain in the range of each other, which in turn affects the sensing process, but this effect has overall a limited impact.

Since the settings for 5G NR-V2X are still debated, in line with LTE-V2X we assume SCS = 15 kHz, with five subchannels of 10 PRBs each; this implies slots of 1 ms. Results will be anyway shown also modifying these settings to demonstrate that they are of wider validity. The transmission power is set to 23 dBm [13,20], the antenna gain to 3 dBi at both the transmitter and receiver and the noise figure of the receiver to be 9 dB, which are values commonly used [36] and consistent with real devices. Similarly to other works on NR-V2X sidelink (e.g., [37,38]), the path-loss model follows the WINNER+, scenario B1, under line-of-sight (LOS) conditions, with correlated log-normally distributed shadowing with standard deviation of 3 dB and decorrelation distance of 25 m [39].

The keep probability p_k is set to 0.4 [40]. The RSRP sensing threshold, used to identify busy subchannels, is equal to −126 dBm [19], and the delay budget is constrained between 1 and 100 ms. The MCS 11 is used, corresponding to the most reliable one to allocate 1000 bytes in one slot; this implies that each transmission is performed over five subchannels. The correct reception of each packet is detected based on a SINR threshold set to 9.95 dB [41]. In the case of retransmissions, maximum ratio combining (MRC) is applied at the receiver. When the FD capability is used, it also allows the transmitting VUE to concurrently detect and decode a message if a message is present and characterized by a sufficient SINR after SI cancellation. However, the impact of this capability is negligible, as already discussed in Section 2.3.

4.3. Benchmarks

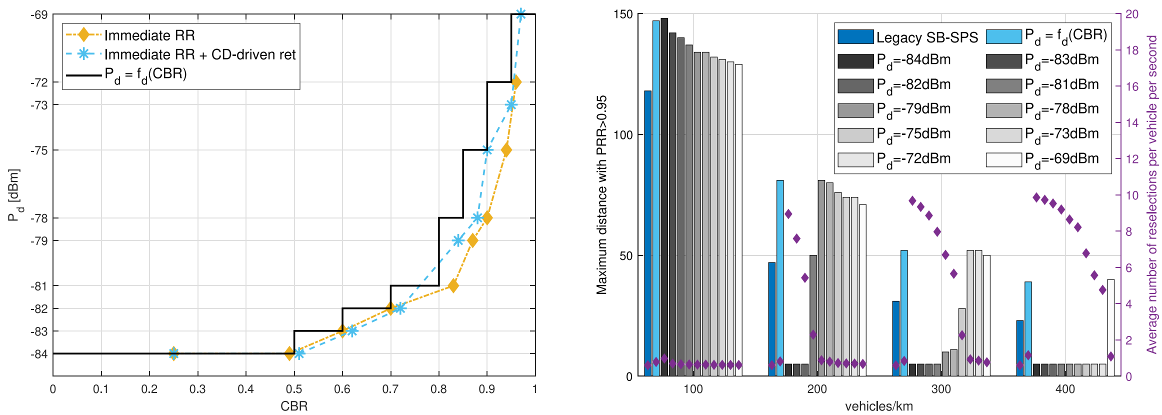
The performance of the proposed scheme is compared against the following benchmarks: *(i)* the legacy SB-SPS leveraging HD transceivers and *(ii)* the solution proposed in [7], on top of Mode 2, that we name here *adaptive* p_k, as a representative of FD-based solutions in the literature. Adaptive p_k triggers the resource reselection only when the RC reaches zero. In particular, for a given VUE, the probability p_k is dynamically set equal to:

$$p_\mathrm{k} = 1 - \frac{\sum_{n=1}^{n_\mathrm{SPS}} \delta_\mathrm{col}^{(n)}}{n_\mathrm{SPS}}, \tag{10}$$

being $\delta_\mathrm{col}^{(n)}$ the collision detection flag, which is a Bernoulli variable, tracking if a collision occurred or not at current iteration n during the reservation period.

4.4. Metrics

The performance is assessed in terms of the following metrics:



(a) Optimal values of the P_d threshold vs. CBR with two specific configurations (non-solid curves), and function $f_d(CBR)$ adopted in the CD3R MAC scheme (solid curve).

(b) Maximum distance with PRR>0.95, assuming legacy SB-SPS, $P_d = f_d(CBR)$, or fixed values of P_d. Immediate RR coupled with CD-driven retransmission is assumed.

Fig. 8. Tuning of P_d. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

- The PRR, computed as the ratio between the number of VUEs successfully decoding the packets at a given distance from the transmitter and the number of VUEs located at the same distance [34];
- The maximum distance with PRR > 0.95, as used by 3GPP in [42], to assess the range over which messages are transmitted in a sufficiently reliable manner;
- The WBSP, defined in [43] as the probability that, in an observation window, two vehicles cannot receive updates from each other (i.e., no messages are sent, or no messages are correctly received). Indeed, if several consecutive messages are lost from a generic vehicle, the shared information is no longer updated for some time, and that time is here called the wireless blind spot (WBS). The WBSP is calculated considering messages exchanged among vehicles at reciprocal distances that are not longer than 150 m.

5. Evaluation campaign

A comprehensive evaluation campaign has been conducted, which aims to determine the proper settings of the proposed CD3R scheme. The study also investigates the applicability of the scheme to VUEs with less accurate SIC capabilities. Finally, the study focuses on comparing the performance of the different configurations of the scheme against the selected benchmarks and with each other, under a wide variety of settings, determining which is more suitable for each scenario.

5.1. Tuning of the collision detection threshold

As mentioned in Section 3.2, the performance of the proposed CD-based algorithm is affected by the setting of the parameter P_d. In this work, we set it dynamically according to the perceived channel congestion measured through (6). In order to determine the best setting of P_d, we assumed all VUEs adopt the same and fixed P_d, and we ran different simulations when varying it under different traffic densities and, consequently, different CBR values.

Fig. 8(a) reports, when varying the CBR, the values of P_d that maximize the distance with $PRR > 0.95$ for two configurations of CD3R. More specifically, the yellow and light blue curves in Fig. 8(a) correspond to the optimal P_d settings for the Immediate RR configuration alone and the Immediate RR configuration combined with the CD-driven retransmission, respectively. Interestingly, no remarkable differences in terms of optimal values of the P_d thresholds are experienced for the two different configurations. Hence, the P_d thresholds can

Table 4
CBR and average number of reselections per vehicle per second when varying P_d and vehicle density ([vehicles/km]). Immediate RR coupled with CD-driven retransmission is assumed.

Scheme	CBR				Reselections/vehicle/s			
	100	200	300	400	100	200	300	400
Legacy SB-SPS	0.48	0.81	0.93	0.98	0.60	0.60	0.59	0.60
$P_d = f_d$(CBR)	0.50	0.84	0.95	0.98	0.78	0.81	0.84	1.15
$P_d = -84$ dBm	0.51	0.80	0.90	0.91	0.97	8.94	9.67	9.86
$P_d = -78$ dBm	0.48	0.83	0.94	0.96	0.63	0.80	5.65	8.21
$P_d = -69$ dBm	0.48	0.82	0.94	0.98	0.62	0.67	0.76	1.09

be robustly set the same for both schemes. In particular, the black curve represents the final relationship between P_d and CBR, where the chosen thresholds for the setting of P_d have been intentionally set higher than the reference values to be more conservative, as explained hereafter.

Fig. 8(b) shows with a bar plot the maximum distance with $PRR > 0.95$ (left y-axis) when varying the vehicle density for different (static) settings of P_d (different gray scales) and when applying the dynamic CBR-driven threshold through the proposed function $P_d = f_d(CBR)$ (light blue bar). The Immediate RR coupled with CD-driven retransmission is considered here, and the legacy SB-SPS is reported as a benchmark (blue bar). The same plot also shows with diamond markers the average number of reselections per vehicle per second (right y-axis). Looking at the bars of Fig. 8(b), it can first be observed that with the proper setting of P_d, a great improvement can be obtained by the proposal w.r.t. the legacy SB-SPS for all traffic densities. It can also be noted that the performance of the proposal is quite sensitive to the setting of P_d: in fact, under high-density settings, a too low value of P_d results in too many reselections (even more than 5 per vehicle per second), thus cancelling the benefits of the SB-SPS scheme; this eventually leads to worse reliability. On the opposite, when the threshold is set to a too high level, the effectiveness of CD reduces. Relevantly, whereas a threshold slightly lower than the optimal one significantly impacts the performance, a slightly higher value has a small impact, which justifies the choice discussed in Fig. 8(a). Finally, when looking at the performance with an adaptive $P_d = f_d(CBR)$, under all density scenarios the proposal behaves similarly to the optimal and fixed P_d case. This trend confirms that the solution accounting for the CBR to set P_d is able to flexibly and effectively adapt to different traffic scenarios.

The effectiveness of the adaptive threshold setting is also confirmed focusing on the average number of reselections indicated by diamond markers in Fig. 8(b) and further deepened in Table 4. In the legacy SB-SPS procedure, a vehicle maintains a selected resource according to the reselection counter which is randomly initialized within a certain range, which is between $n_{\min} = 5$ and $n_{\max} = 15$ for an RRI equal to $T_{\mathrm{RRI}} = 100$ ms. Then, statistically, after the reselection counter expires it may maintain the resource again with probability p_{k}. Therefore, the average number of consecutive transmissions before changing the resources $E\left[n_{\mathrm{BC}}\right]$ can be calculated as (the reader can refer to [43] for additional details)

$$E\left[n_{\mathrm{BC}}\right] = \frac{n_{\max} + n_{\min}}{2} \frac{1}{1 - p_{\mathrm{k}}} \tag{11}$$

and the average number of reselections per vehicle per second $\overline{q}$ becomes

$$\overline{q} = \frac{1}{T_{\mathrm{RRI}}\ E\left[n_{\mathrm{BC}}\right]} = \frac{2\left(1 - p_{\mathrm{k}}\right)}{T_{\mathrm{RRI}}\left(n_{\max} + n_{\min}\right)}. \tag{12}$$

With the settings used in this work, this results in an average reselection rate of $\overline{q} = 0.6$. Please note that this value is independent from the vehicle density.

In the proposed schemes, more reselections can occur due to detected collision, with a lower bound of 0.6. Given that packets are generated every 100 ms, the maximum possible number of reselections per second is 10, corresponding to a scenario where every vehicle selects a new resource after each transmission. With FD-based reselections, the vehicle density can indirectly impact on the number of reselections, since a larger number of vehicles implies an increase of the overall channel occupation, which in turn can increase the number of detected collisions. This can indeed be observed by looking to Table 4. The table confirms that the average number of reselections per vehicle per second is constant and close to 0.6 when the legacy SB-SPS is assumed, while it is larger when FD-based reselections are considered. It can also be observed that with FD the reselections increase with the channel occupation and that, when P_{d} is fixed, the increase is more pronounced with lower values of the threshold. Remarkably, with the dynamic setting of P_{d}, the increase of the average number of reselections is limited, even for large values of the CBR.

5.2. Impact of SI cancellation capability

In this paper, results are provided assuming $K_{\mathrm{SI}} = -110$ dB, which is considered the best SI cancellation factor according to recent studies [44,45]. To further discuss this aspect, in this section a different value of K_{SI} is also considered to infer the applicability of the proposed solution to less accurate FD transceivers.

In Fig. 9, results assuming either $K_{\mathrm{SI}} = -110$ dB (light blue bars) or $K_{\mathrm{SI}} = -100$ dB (gray bars) are compared and also benchmarked against the legacy SB-SPS (blue bars). Results are shown for three values of the density using per each one the best value of P_{d}. As expected but here confirmed by results, for a given density setting, the results corresponding to different SIC capabilities can be fairly compared if the value of P_{d} is the same. By exploiting this conclusion, the results obtained assuming a given known value of K_{SI} are also representative of any other value of K_{SI} for which that value of P_{d} is possible, where P_{d} is possible if it is above the residual SI (see (5) in Section 3.1).

5.3. The CD3R MAC scheme vs. benchmark solutions

The second set of results compares the proposal's performance against the considered benchmark schemes, in terms of PRR and WBSP, under low and high vehicle density settings. For the sake of a fair comparison, P_{d} is dynamically set as reported in Fig. 8(a) for all the compared schemes. The WBSP is observed from a minimum of 200 ms, since it is the minimum window to include at least two transmissions.

Fig. 10 shows the PRR vs. distance (Fig. 10(a)) and the probability of a given WBS (Fig. 10(b)), assuming low vehicular density, i.e., 50 vehicles/km. As observable, under low density settings, Immediate RR with Single CD achieves the highest PRR values. This is because in such a scenario the use of retransmissions is beneficial to increase the reliability. Moreover, reacting with a reselection upon at least one detected collision allows to break persistent collisions.

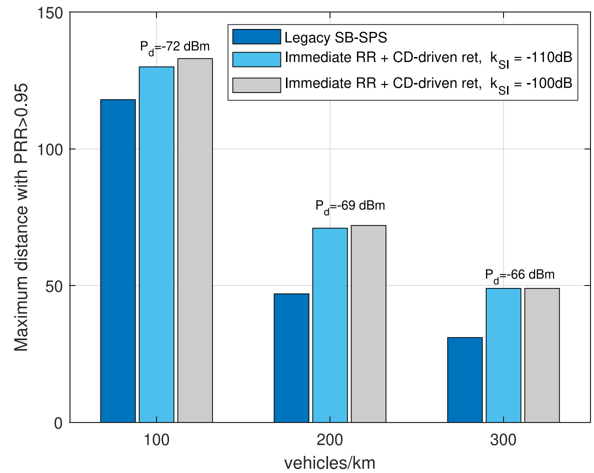


Fig. 9. Maximum distance with $PRR > 0.95$ for the immediate RR + CD-driven ret, when varying the vehicle density and considering different SIC capabilities. The first bar, for each density, reports results for the legacy SB-SPS and the other two bars of each density correspond to two values of K_{SI} but the same detection threshold as reported in the figure. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

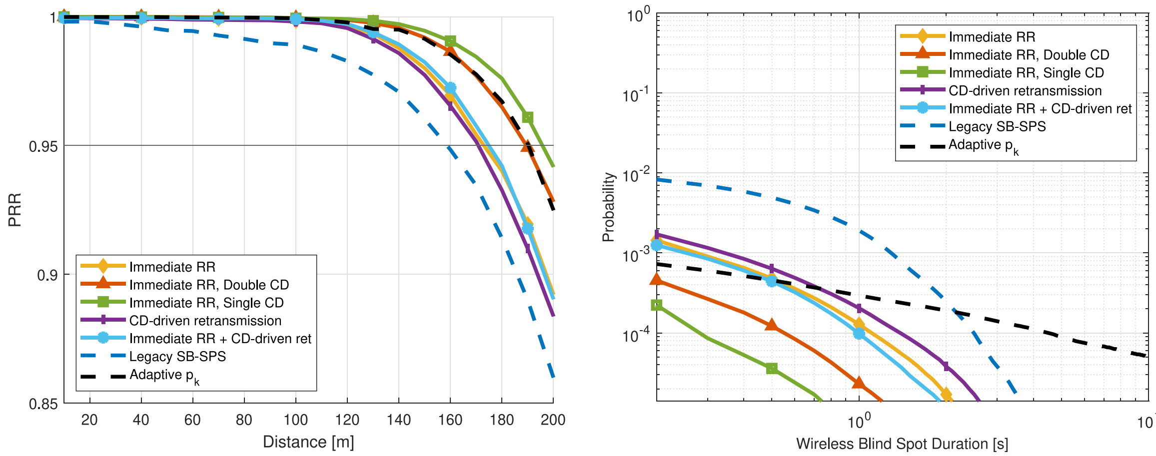
Interestingly, the adaptive p_{k} benchmark approaches the performance of the immediate RR, Single CD.

Such a trend is because, under low congested scenarios, vehicles exhibit very few collisions; hence, p_{k} is mostly set near 1. By letting VUEs keep the same resources for several consecutive transmissions, the sensing of the SB-SPS is effective. However, in the few cases when two VUEs select the same resource, this causes very long bursts of consecutive errors. Indeed, as can be observed in Fig. 10(b), the performance in terms of WBSP gets worse for long durations of WBS since long bursts of errors can occur with a rather high probability.

Under higher density settings, i.e., 200 vehicles/km in Fig. 11, the benefits of retransmissions get smaller, especially at large distances. Retransmissions contribute, in fact, to increase the overall congestion. Therefore, it is better to adopt a configuration which lets each VUE use a single resource at each message transmission and react in case of collision detection through resource reselection and retransmission. This is what is foreseen by Immediate RR, possibly when coupled with the CD-driven retransmission. As shown in Fig. 11(a), the latter configuration is, in fact, the solution that provides the highest PRR values under all transmitter–receiver distances. It can also be noted that the improvement is especially visible at short distances, where interference and consecutive collisions have a higher impact than losses due to radio propagation dynamics.

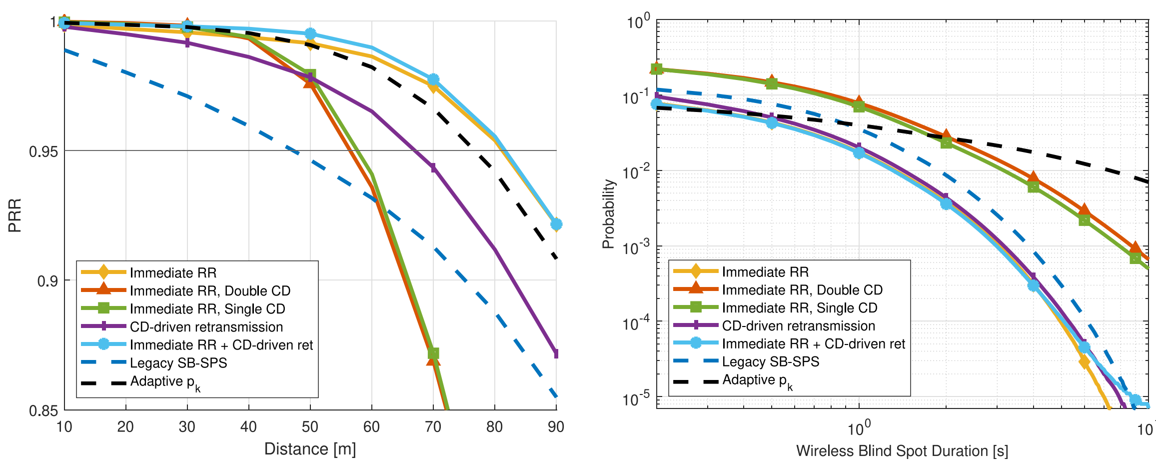
Again, the adaptive p_{k} achieves good performance in terms of PRR, which approaches that of Immediate RR coupled with the CD-driven retransmission, but it results in possible long bursts of collisions, as shown in Fig. 11(b).

Fig. 12 shows the performance of all the compared configurations for a wide variety of traffic densities. In particular, Fig. 12(a) reports the maximum distance that can be achieved with PRR above 0.95, whereas Fig. 12(b) provides the WBSP for a WBS of 5 s. First of all, it can be observed that the legacy SB-SPS is always among the worse solutions, both in terms of PRR and WBSP. The adaptive p_{k} appears near to the best in terms of PRR but near to the worst in terms of WBSP. Looking at the CD3R MAC scheme when the traffic density is low, the best performing configurations, both in terms of PRR and WBSP,



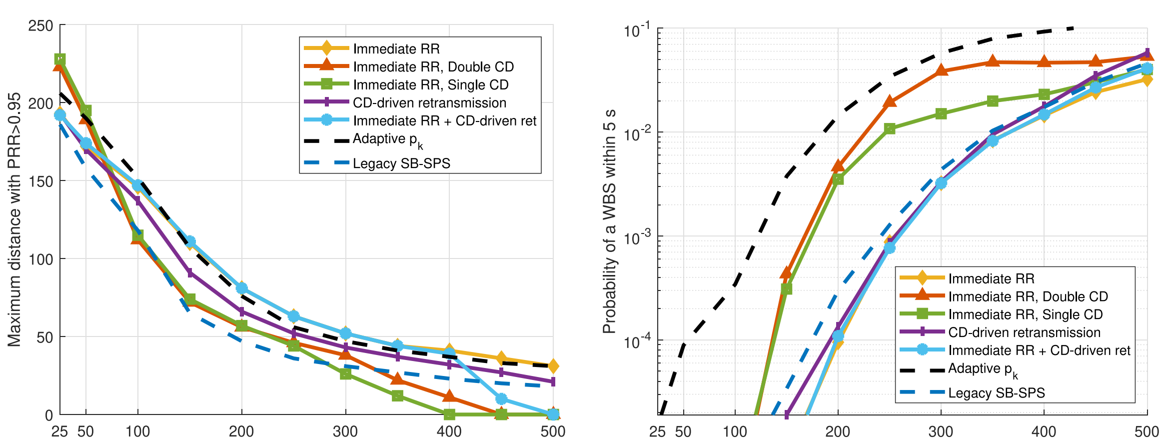
(a) PRR. (b) WBSP.

Fig. 10. PRR and WBSP for different MAC schemes and configurations (50 vehicles/km).



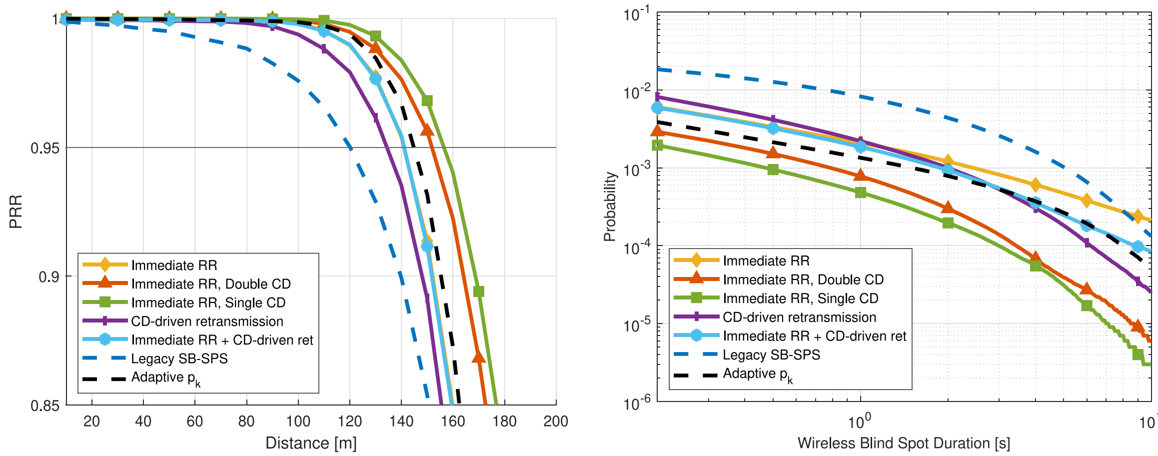
(a) PRR. (b) WBSP.

Fig. 11. PRR and WBSP for different MAC schemes and configurations (200 vehicles/km).



(a) Maximum distance with $PRR > 0.95$. (b) WBS probability of $5s$.

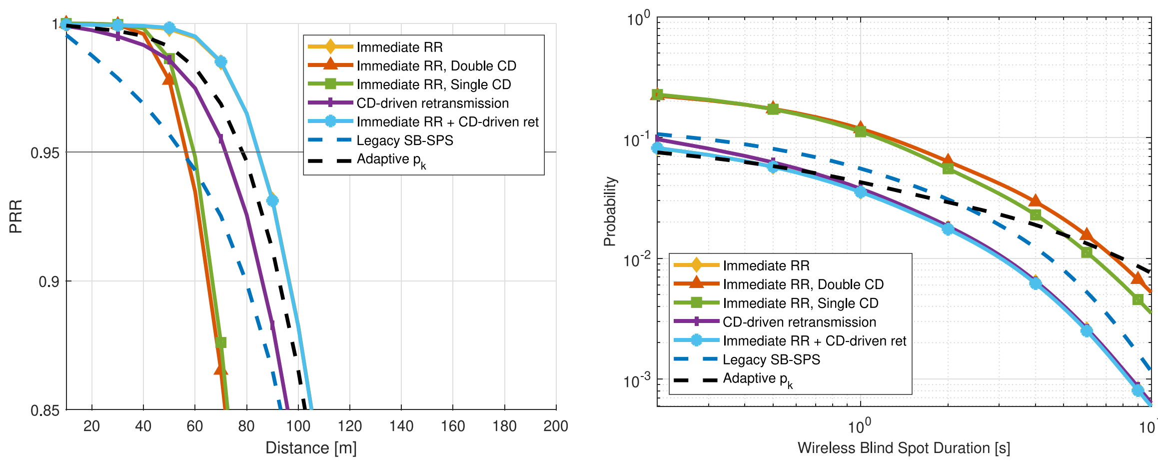
Fig. 12. Maximum distance with $PRR > 0.95$ and WBSP for different vehicle densities and different MAC schemes and configurations.



(a) PRR.

(b) WBSP.

Fig. 13. PRR and WBSP for different MAC schemes and configurations, when considering 20 MHz bandwidth and SCS 30 kHz (100 vehicles/km).



(a) PRR.

(b) WBSP.

Fig. 14. PRR and WBSP for different MAC schemes and configurations, when considering 20 MHz bandwidth and SCS 30 kHz (400 vehicles/km).

are those which always enforce retransmissions, i.e., Immediate RR with Single CD and Immediate RR with Double CD; the former, which implies a higher probability of reallocation, slightly outperforms the latter. With traffic densities higher than 100 vehicles/km, Immediate RR and the same configuration coupled with CD-driven retransmissions outperform the other configurations which always enforce retransmissions, again both in terms of PRR and WBSP. Coherently with this observation, CD-driven retransmissions are helpful under medium to high density settings but are preferably deactivated when the channel tends to be congested (i.e., starting from 400 vehicles/km). Indeed, under such settings a PRR lower than 0.95 can be only ensured, which is not acceptable.

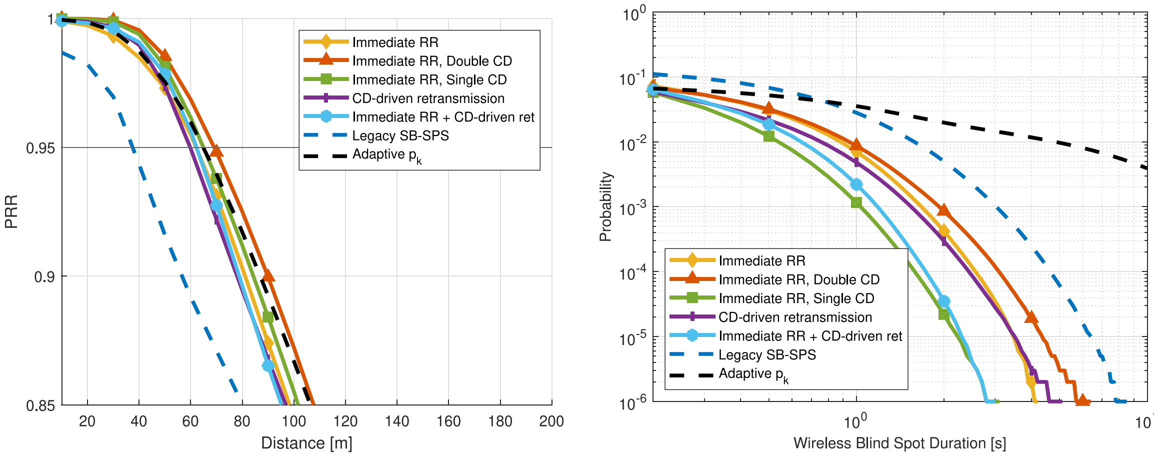
5.4. Validity of the results with different settings

With the aim to validate the conclusions beyond the specific settings, additional results are provided in Figs. 13, 14, and 15 as detailed in the following.

Larger channel bandwidth. In Figs. 13 and 14 transmissions occur within a 20 MHz channel bandwidth, which is what currently proposed by part of the industry for the use of 5G NR-V2X. Following the indications in ETSI 303 798 [46], five subchannels of 10 PRBs each are assumed in the 20 MHz channel, with an SCS of 30 kHz, which implies slots of 0.5 ms. Results are reported for 100 vehicles/km and 400 vehicles/km to resemble low and high vehicular density settings. Values are doubled compared to the ones reported in the previous Section to consistently account for the doubled bandwidth.

Overall, results are consistent with those achieved when considering 10 MHz, even if the doubled bandwidth causes an increase of the noise, which in turn reduces the range. In particular, similar to the results discussed in the previous section, under low vehicular density settings (100 vehicles/km, Fig. 13(a)), Immediate RR with Single CD achieves the highest PRR values, thanks to the enforcement of retransmissions, which are particularly beneficial when the channel load is low. Under higher density settings (400 vehicles/km, Fig. 14(a)), the benefits of retransmissions get smaller; in this case, the Immediate RR, possibly when coupled with the CD-driven retransmission, is again the scheme which achieves the best performance (see also Fig. 14(b)).

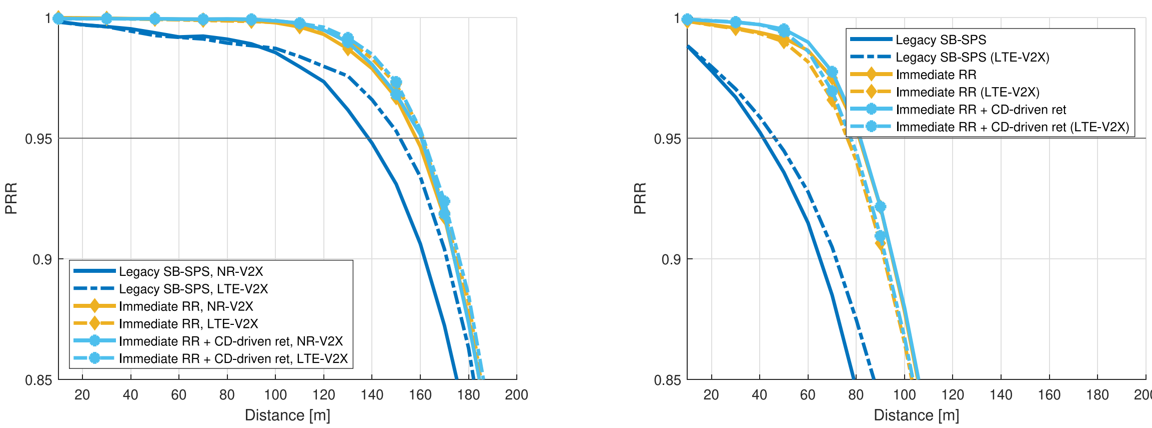
Smaller packets. In Fig. 15, results are shown adopting again 10 MHz channel and SCS of 15 kHz, but assuming transmissions that use only one out of five subchannels. This is achieved by assuming packets of 140 bytes (i.e., smaller than one fifth of 1000 bytes, due to a larger impact of the control overhead). With the aim to obtain similar average number of transmissions per subchannel per unit of area than the case of Fig. 10, we have simulated five times the density, i.e., 250 vehicles/km. What can be observed is that also in this case, all the FD-based solutions significantly outperform the legacy SB-SPS, both in terms of PRR and WBSP. Even if the results are consistent with what



(a) PRR.

(b) WBSP.

Fig. 15. PRR and WBSP for different MAC schemes and configurations, when considering 250 vehicles/km and transmissions using one subchannel out of five.



(a) 50 vehicles/km

(b) 200 vehicles/km

Fig. 16. Comparison in terms of PRR vs. distance between LTE-V2X and NR-V2X when considering some of the discussed FD collision detection schemes. The NR PHY layer is assumed in LTE-V2X with the scope to focus only on the MAC procedures.

observed in Fig. 10, similar values of the PRR are obtained in Fig. 15(a) at shorter distances; this is because transmissions occupying different subchannels, but in the same slot, partly interfere with each other due to the IBE, i.e., the residual power in the adjacent bands.

5.5. Applicability to LTE-V2X

Considering that the comparison between LTE-V2X and NR-V2X is not extensively explored in the literature, and even if a thorough analysis of the differences between these two technologies is beyond the scope of this work, this section briefly discusses the applicability of the proposed schemes also to LTE-V2X. From the perspective of resource allocation procedures, the primary difference between LTE-V2X and NR-V2X stems from the support for aperiodic transmissions introduced in NR-V2X. To better handle this type of traffic, certain procedures in LTE-V2X have been modified. Specifically, NR-V2X has removed the averaged sensing procedure and the so-called L2 list, as discussed in [19]. In LTE-V2X, the interfering power for each resource is estimated based on past data, assuming periodic traffic. Resources are then sorted by the estimated interfering power in the L2 list. Conversely, NR-V2X follows the procedure summarized in Section 2.1. For periodic traffic, such as in this study, the overall impact of the sensing and reservation procedure is similar for both technologies. Therefore, collision detection procedures based on full-duplex benefit both LTE-V2X and NR-V2X without significant differences. To confirm this claim, results shown in Fig. 16 compare the performance of LTE-V2X and NR-V2X when considering two of the proposed FD MAC schemes (Immediate RR and Immediate RR + CD driven retransmission), either assuming 50 or 200 vehicles per km and looking at the PRR varying the distance. For the sake of a fair comparison and with the aim to focus solely on the resource allocation, we made them equivalent at the PHY layer: in particular, we considered for LTE the same MCS and transport block size determination as from NR-V2X procedures, and we assumed the same SINR threshold.[5] With these assumptions, LTE differs from NR-V2X only for the resource allocation procedure which consider the L2 list and the averaged sensing, making their impact easier to observe. Looking at Fig. 16, it can be seen that the performance is very similar. When observing the curve for the legacy SB-SPS (without FD) it can be noticed that the LTE-V2X resource allocation tends to perform slightly better. This is due to the use of the L2 list, which passes to the higher layer always the least interfered resources. However, when looking at the curves related to the FD-based schemes, the opposite can be observed. In such case, in fact, more reselection occurs due

[5] Please notice that the considered settings are not intended to enable a direct comparison between the vanilla LTE-V2X and NR-V2X autonomous approaches, but instead to showcase the benefits of the proposed FD schemes on both technologies, while capturing their peculiar differences in the MAC procedures.

Table 5
Summary of the main trends of the compared solutions.

	Low density	Medium density	High density	Congestion
CD3R	*Immediate RR, Single CD* best in PRR and WBSP	*Immediate RR + CD-driven ret* among best PRR, best WBSP	*Immediate RR + CD-driven ret* best in PRR and WBSP	*Immediate RR* best in PRR and WBSP
Adaptive p_k	Near best PRR, but worst WBSP	Among best PRR, but worst WBSP	Near best PRR, but worst WBSP	Mid PRR and worst WBSP
Legacy SB-SPS	Worst PRR and bad WBSP	Worst PRR and bad WBSP	Worst PRR and mid WBSP	Bad PRR and mid WBSP

to the collision detection; with more reselections, it is more likely that the sensing process of LTE-V2X includes outdated values of the resource occupation. In NR-V2X, only the measurements corresponding to the latest transmissions are used for resource selection and this makes NR-V2X less affected by the increase of the resource reselection frequency.

5.6. Main findings

The main findings deriving from the shown results are summarized in Table 5, where the CD3R MAC scheme is compared with the selected benchmarks for various traffic densities. Overall, the results provided show that the proposed CD3R MAC scheme yields a significant improvement compared to the legacy SB-SPS for all densities and in terms of both PRR and WBSP, while compared to the Adaptive p_k it shows an improvement in terms of PRR, which is small in some cases but always coupled with a significant improvement in terms of WBSP.

Looking at the possible configurations of the CD3R MAC scheme, the results highlight that moving from a sparse to a congested traffic scenario, the optimal solution corresponds to a decreasing number of retransmissions. In fact, by examining Fig. 12 and following the first row of Table 5, when the density is low, the best configuration is the one with the highest number of retransmissions and triggering the highest number of reselections (i.e., the best is Immediate RR, Single CD). Then, when increasing the traffic density, continuous retransmissions should be avoided and they should only be triggered when needed (i.e., the best is Immediate RR + CD-driven retransmissions). When the channel becomes congested, then no retransmissions should be enforced, and the system should only rely on the immediate reallocation to reduce the probability of long bursts of collisions (i.e., the best is Immediate RR).

6. Conclusion and future work

In this paper, we proposed a novel MAC scheme aimed at improving the performance of the sidelink autonomous mode when serving periodic traffic via SB-SPS, through FD-triggered resource reselection and retransmissions. Upon collision detection, the proposal is meant to *(i)* break persistent collisions by triggering resource reselection and *(ii)* recover from packet losses by performing a retransmission. To improve the effectiveness of collision detection under different traffic conditions, the relevant threshold is dynamically set according to the measured channel congestion. Extensive simulations were conducted under various vehicle densities, with different configurations of the proposed scheme, with and without blind retransmissions. The results proved the benefits of the proposal and its superiority compared to other benchmarks by also providing indications of the best configuration when varying the traffic density. The proposal shows promising results in the wide range of considered scenarios and opens the way for additional studies investigating potential synergies with ongoing standardization efforts. In particular, the proposal is supposed to complement the IUC in scenarios where broadcast and unicast/groupcast communications coexist. Moreover, achieved findings pave the way for coupling the CD3R MAC scheme with legacy congestion control mechanisms, which allow enabling and disabling retransmissions according to the measured channel load. Future work is planned to extend the solution to situations where also aperiodic generation of packets is considered.

CRediT authorship contribution statement

Vittorio Todisco: Writing – original draft, Validation, Software, Methodology, Investigation, Conceptualization. **Claudia Campolo:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Conceptualization. **Antonella Molinaro:** Writing – review & editing, Supervision, Conceptualization. **Antoine O. Berthet:** Writing – review & editing, Conceptualization. **Richard A. Stirling-Gallacher:** Writing – review & editing, Conceptualization. **Alessandro Bazzi:** Writing – review & editing, Writing – original draft, Supervision, Software, Methodology, Investigation, Formal analysis, Conceptualization.

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

Data will be made available on request.

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