Mitigating Collisions in Sidelink NR V2X: A Study on Cooperative Resource Allocation

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***Abstract*—New Radio (NR) Vehicle-to-Everything (V2X) Sidelink (SL), an integral part of the 5G NR standard, is expected to revolutionize the automotive and rail industries by enabling direct and low-latency exchange of critical information between traffic participants independently of cellular networks. However, this advancement depends primarily on efficient SL resource allocation. Mode 2(a) is a well-known method for this purpose, where each node autonomously selects resources. However, this method is prone to packet collisions due to the hidden-node problem. In this paper, we propose a cooperative scheduling method that could potentially address this issue. We describe an extension of Mode 2(a) that allows nodes to share resource allocation information at two hops. Initial simulation results show a promising improvement over Mode 2(a).**

***Index Terms*—NR V2X, Sidelink communications, Cooperative resource scheduling, Packet collision, Ad-hoc network, 5G.**

I. INTRODUCTION

5G New Radio (NR) Vehicle-to-Everything (V2X) communication is a cutting-edge technology that is expected to revolutionize the automotive industry and transportation systems [1]. It is a subset of the 5G NR standard designed to enable direct data exchange via Sidelink (SL) communication. In particular, SL is an essential component within the NR V2X ecosystem, specifically designed to enable direct communication between vehicles, road infrastructure, and other road users without the involvement of the base station. This enhances road safety, enabling features such as collision avoidance, blind spot warnings, and intersection coordination, making roads safer for everyone while paving the way for the future of connected and autonomous vehicles.

Resources in NR V2X SL are allocated by the gNodeB when using Mode 1 operation, or autonomously selected by each vehicle from a predefined pool of resources when using Mode 2 operation mode. In Mode 2, and more specifically Mode 2(a), resource allocation is performed using the sensing-based Semi-Persistent Scheduling (SPS) and Dynamic Scheduling algorithms [1], which allow autonomous resource selection for multiple transmissions of Transport Blocks (TBs) and real-time adaptation for each TB transmission, respectively [2].

Although NR V2X was originally designed for vehicular applications, it has recently been identified as a potential enabler for Next-Generation Train Control and Monitoring Systems (NG-TCMSs) [3] as well. Specifically, NR V2X could be utilized to create the WireLess Train Backbone (WLTB) and WireLess Consist Network (WLCN) in future railway networks. To meet the industrial-like communication requirements over multiple hops in railway networks, a mesh topology architecture is necessary (considering railway networks are not fully covered by infrastructure-based 5G connectivity). However, NR V2X Mode 2(a) does not provide the collision-free and deterministic communication that is required by WLTB and WLCN. One of the main challenges is the hidden-node (terminal) problem that can significantly degrade system performance.

In recent years, cooperative resource scheduling has been introduced to enhance the performance of autonomous resource selection in Mode 2 [4]. The newly included sub-modes, specifically Mode 2(b), Mode 2(c), and Mode 2(d) extend Mode 2(a) by enabling nodes to assist each other in determining which resources should or should not be considered as candidates for certain nodes. However, the description of these modes appears to be generic and lacks a deterministic definition. It also lacks technical details to fully characterize each mode. In fact, it has been argued that the current description fails to distinguish each mode from other modes [5], [6]. Additionally, it is unclear whether these modes preserve the feature of channel sensing and autonomous channel selection, similar to Mode 2(a).

This paper takes a step towards realizing cooperative resource allocation for NR V2X Mode 2. We propose a method for alleviating the negative impact of packet collisions by sharing information among transmitting nodes. Periodically broadcasting the list of unavailable resources detected by each node during the channel sensing process achieves the propagation of information regarding the unavailable resources up to two hops, addressing the hidden-node problem. In this paper, we provide a preliminary performance evaluation of this approach and discuss its potential, but also the limitations and possible improvements.

The paper is structured as follows. Section II provides additional information on Modes 2(a)-2(d) and technical concerns discussed in the literature. In Section III, we present our solution for cooperative resource scheduling by disseminating resource occupation information throughout the network. Section IV presents the simulation evaluation to demonstrate the effectiveness of the proposed solution in relation to Mode 2(a). Finally, Section VI concludes the work, highlights its findings, and identifies future extensions.

II. NR V2X SIDELINK COMMUNICATION

In this section, we provide a detailed description of the different operation sub-modes for autonomous resource allocation in NR V2X SL communications.

A. Mode 2(a)

This mode explores SL sensing and resource selection in two different contexts [1]: an SPS scheme, where resources are allocated for periodic transmissions of different TBs, and a dynamic scheme, where resources are selected for each TB transmission individually. Methods used to identify occupied SL resources include decoding SL control channel transmissions, SL measurements, and detecting SL transmissions. The main goal is to improve communication reliability and reduce the collision probabilities by utilizing techniques such as sensing, reservation, and Listen-Before-Talk (LBT).

A candidate resource will be excluded from the pool of available resources if two conditions are met: 1) the User Equipment (UE) estimates that a neighboring UE intends to use the candidate resource based on the received Sidelink Control Information (SCI), either in the current selection window or for upcoming TBs; 2) if the average Reference Signal Received Power (RSRP) measured over the TB associated with the corresponding SCI is higher than a threshold.

According to [7], there are four main types of packet errors that quantify the system performance loss in Mode 2(a):

1) Errors due to half-duplex transmissions;
2) Errors due to a received signal power below the sensing power threshold;
3) Errors due to propagation effects, where a packet is received with a signal power higher than a required threshold, but the received Signal-to-Noise-Ratio (SNR) is not sufficient;
4) Errors due to packet collisions.

The first three types of errors are caused by environmental factors such as pathloss and shadowing, as well as the Modulation and Coding Scheme (MCS). The fourth type of error is inherent to the resource allocation offered by Mode 2(a) and is due to the autonomous nature of resource selection without full knowledge of resources selected by other nodes. As mentioned in Section I, this is referred to as the hidden-node problem.

B. Mode 2(b)

In this mode, the UE assists in SL resource selection for other UEs by sharing additional information, such as sensing or interference measurements. Assistance information types, as described in [5], [8]–[10], include location, velocity, traffic priority, congestion or occupancy information, and RSRP. The provided information includes Channel State Information (CSI) and feedback reports, Quality of Service (QoS) information, and information on occupied/reserved SL resources from other UEs, as well as reports of sensing results.

C. Mode 2(c)

In this mode, the UE is configured with NR configured grant for SL transmission [10]. For out-of-coverage operation, this mode assumes a pre-configuration of single/multiple SL transmission patterns defined on each SL resource pool (a pattern is defined by the size, position and the number of the resource in time and frequency). For in-coverage operation, this mode assumes that the network reasonably assigns single/multiple SL transmission patterns defined on each SL resource pool to the UEs [5]. For a single configured pattern, there is no sensing procedure performed by the UE, while for multiple configured patterns, some form of sensing may be used (especially in periodic traffic scenarios) to improve performance. The number of transmissions allowed per transmission pattern should depend on the time-domain length of these patterns and the number of UEs. The length of the transmission patterns (in the time domain) and the Subcarrier Spacing (SCS) will determine the overall latency of the scheme [11].

D. Mode 2(d)

In this mode, a UE, which may have more capabilities than other UEs around it, can perform scheduling functions on behalf of the infrastructure. To do this, the transmitting UE provides information about SL resources to the scheduling UE . The application layer or preconfiguration selects the scheduling UE [8]. Alternatively, the scheduling UE is decided by multiple UEs, including the one that is finally selected. As for group-based SL communication, the scheduling UE informs its serving gNB about other UEs in the group [5], [12]. The gNB provides individual resource pool configurations and/or individual resource configurations to each group member through the scheduling UE. The scheduling UE cannot modify the configurations and no direct connection is required between any member UE and the gNB. Only higher-layer signaling is used to provide the configurations [8]. This functionality depends on the capabilities of the UE.

E. Summary

As can be seen from the descriptions of the Modes 2(b)-(d), the detailed specifications of each mode are yet to be defined. In fact, some recent studies argue for the exclusiveness of these modes. For instance, Mode 2(b) is said to be basically a functionality that can be incorporated into the other modes and rather an enhancement technique that is not supported or studied as a standalone SL resource allocation [6]. According to [5], Mode 2(b) can at best be considered as a variant of Mode 2(d), where a UE schedules SL transmission for another UE. In addition, Mode 2(c) behaves essentially as a Mode 1 UE-configured with the same time/frequency pattern [5] for the in-coverage scenario. Some cooperative methods may not fit exclusively into one mode. For example, consider the case where a receiver UE schedules the transmissions of the transmitter UE during the session by selecting pre-configured transmission patterns as well as using the assisting information (whether sensed or not) from other UEs. It is then obvious that a combination of all of the above modes should be incorporated.

III. COOPERATIVE SCHEDULING IN MODE 2

The hidden-node problem in Mode 2(a) is mainly caused by a UE's lack of knowledge about the resources reserved by other UEs. Although each transmitting UE reports the reservation information, this information reaches the neighboring UEs only within a certain range, which depends on parameters such as transmission power, distance, environment, attenuation, etc.

Therefore, inspired by the high-level descriptions of the cooperative modes in the Sections II-B to II-D, we extend the original Mode 2(a) so that UEs in the vicinity of each other would be able to replicate the information regarding their resource selection. In this way, there is a generally wider awareness range for the UEs in general, which leads to a lower probability of packet collision. To this end, each transmitting node includes the reservation information of its neighboring UEs in its SCI. This information is collected during the sensing window associated with the previous transmission.

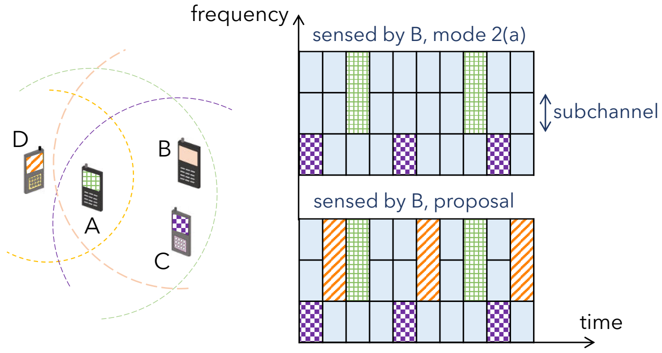

Figure 1. Illustration of resource allocation for Mode 2(a) and the proposed cooperative method.

Figure 1 illustrates an example of this scheme. It is observed that UEs A and D are within each other's coverage radii, while D is outside of the awareness range of B. As a result of this, for the conventional Mode 2(a) (the upper time/frequency resource map in Figure 1), B misses the fact that D is reserving the resources, as shown in the figure in orange color, and it only notices the resources reserved by A and C. In contrast, the cooperative method allows the UE A to also provide B with the information about the reservation made by D. Thus, in the case that both B and D try to transmit to A at the same time, the probability of B selecting the subchannels shown in yellow would decrease, thus reducing the probability of packet collision. From the above explanation, the proposed method is most similar to Mode 2(b) among the extension modes. Nevertheless, we refrain from labeling our method as Mode 2(b) due to a lack of specifications in the original description of Mode 2(b) as mentioned above regarding the channel sensing and selection mechanism.

IV. SIMULATION

In this section, we provide the simulation details adopted for the performance evaluation of the proposed cooperative scheduling mechanism and demonstrate its advantages in relation to Mode 2(a).

A. Simulation parameters and settings

We target the train virtual coupling use case [3] to show the performance of the proposed solution. Figure 2 illustrates the investigated scenario. We consider a single-lane straight railroad where the wagons move at a speed of 70 km/h. A total of 50 and 100 wagons are assumed, with each wagon having a length of 30 m and a distance of 1 m from the adjacent wagon(s).

The selection of a single lane scenario is intentional, aiming to assess the impact of the proposed solution against the hidden-node problem in a controlled testing environment.

The UEs transmit within the 5.9 GHz band with a spectral power density of 13 dBm/MHz. Two scenarios with bandwidths of 10 MHz and 20 MHz are evaluated. The antenna gain is set to 3 dBi for both the transmitter and receiver. A noise figure of 9 dB is assumed at the receiver.

A Line-of-Sight (LoS) communication is considered with a path-loss model following the WINNER+, scenario B1 [13]. The RSRP threshold is set to −126 dBm when not differently specified. The correct reception of each packet is detected based on the Signal-to-Interference-plus-Noise-Ratio (SINR) threshold calculated from the Physical Resource Block (PRB) specifications and the adopted modulation scheme according to [13].

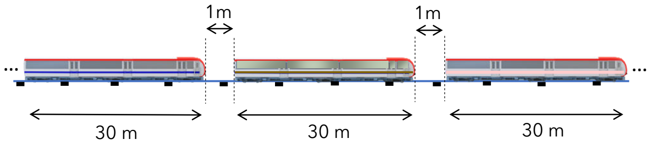

Figure 2. Virtual coupling scenario.

Table I
PARAMETER CONFIGURATIONS

System Parameter	Numerical value
Road layout	straight railway
Number of wagons	50 and 100
Speed of wagons	70 km/h
Antenna gains	3 dBi
Noise figure, N_i	9 dB
Frequency band	5.9 GHz
Bandwidth	10 and 20 MHz
SCS	15 kHz
Channel model	WINNER+ B1
Shadowing	variance 3 dB
Packet generation period	100 ms
Packet size	1000 Byte
Simulation Duration	600 s
RSRP sensing threshold	−126 dBm

In line with [13], [14], packets of 1000 Byte are periodically generated every 100 ms throughout the simulation. For 10 MHz and 20 MHz, an MCS of 11 and 5 are adopted, respectively. A SCS of 15 kHz is assumed for both bandwidths. Table I summarizes the main parameters setting for the simulations.

The extended model has been developed on the open-source simulator WiLabV2Xsim for comparative evaluation with NR V2X Mode 2(a) [13].

B. Performance Evaluation

We evaluate the performance in terms of Packet Reception Ratio (PRR), which is derived as the average ratio between the number of neighbors correctly decoding a message at a given distance and the total number of neighbors at the same distance. Figure 3 illustrates the PRR for different distances and different number of wagons for Mode 2(a) and for the proposed method as explained in Section III. The results are shown for a bandwidth of 10 MHz (top subplot), and 20 MHz (bottom subplot) for MCS of 11 and 5, respectively.

According to Figure 3, the PRR decreases with the distance for both schemes. For Mode 2(a), this is mainly due to the fact that the attenuation of signals, which is proportional to the distance, generally leads to a lower SINR, thus increasing the probability of packet decoding failure upon reception. Furthermore, the hidden-node problem also becomes more troublesome by the distance, as there would be a higher chance for the sensing UE to miss out the resource reservation information of the neighboring UEs during the sensing period. While the first mentioned cause is also present in the case of the proposed scheme, the hidden-node problem becomes less prominent thanks to the added information sharing property. Overall, it is observed that the proposed scheme significantly increases the PRR with respect to Mode 2(a).

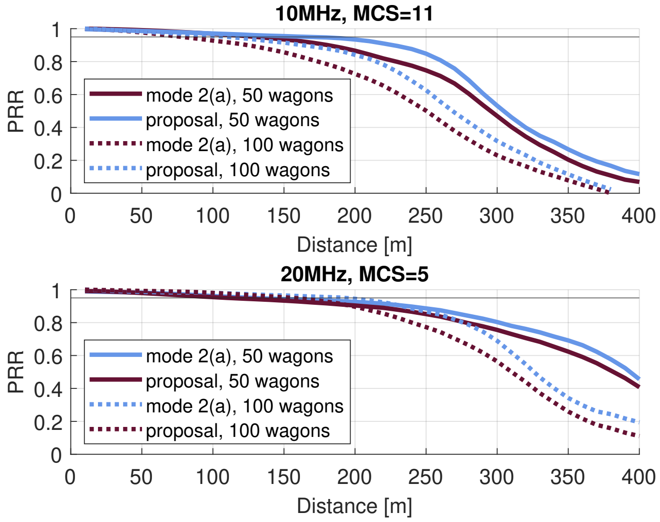

Figure 3. PRR versus distance from transmitting UE.

Another observation is that, for Mode 2(a), there is often a decrease in the PRR with the number of wagons in the scenario. This is due to a higher concentration of interference on the channel. However, for the proposed scheme, the overall trend is the result of a trade-off between the unfavorable increase in interference and yet the favorable increase in the feasibility of spreading the channel reservation information over the network. Due to the fact that signal attenuation is a more dominant factor at longer distances, and given a higher concentration of interference with a larger number of users, it can be seen in Figure 3 that the decrease in the PRR with distance becomes faster for the dotted line (100 wagons) compared to the solid line (50 wagons).

V. DISCUSSION

In this preliminary work, we proposed sharing the list of occupied resources that each UE acquires during sensing and showed the potential of this approach on the PRR. However, including this information in the broadcast messages exchanged periodically increases their size which, in turn, can have a negative impact on the collision probability and channel load. Thus, a more detailed analysis is required to fully understand the impact of this approach on other relevant metrics.

In line with the current status of the research conducted on Modes 2(b)-2(d), it is also essential to further characterize several major aspects for each mode as follows [5]-[12]:

- For Mode 2(b), the following concerns apply: UE behavior and physical channel for delivering and receiving the assistance data, which/whether assistance information is applied for unicast, groupcast, broadcast type of communication or their combination, which assistance information is used and how it is acquired, which UE sends assistance information.
- For Mode 2(c), pattern design in time and frequency for periodic and aperiodic traffic as well as pattern selection procedure by UE should be investigated.
- For Mode 2(d), the main aspects include initialization of operation, behavior of scheduling UE and signaling mechanism to schedule SL resources for transmission and/or reception for other UEs, specification of use cases/scenarios where this mode is applicable, deciding which scheduling UE to schedule which other UE(s) and how to maintain this relationship, realization of the procedure and UE behavior of UE(s) when the scheduling UE disappears, procedures to become/serve as a scheduling UE for in-coverage and out-of-coverage scenarios, relationship between scheduling UE and UE groups from upper layer perspective, whether g-NodeB (gNB) designates the scheduling UEs and how to select a scheduling UE within a group of users that are out-of-coverage, the type of UE scheduling (dynamic or through configured grant), whether a UE should autonomously decide to serve as a scheduling UE (self-nomination) and offer scheduling UE functions.
- On top of all, procedures to switch between these modes also needs to be carefully studied.

VI. CONCLUSIONS

In this work, we investigated the impact of a cooperative resource allocation scheme in 5G New Radio (NR) Vehicle-to-Everything (V2X) Sidelink (SL) to mitigate the impact of the hidden-node problem. In particular, while preserving the conventional resource sensing and selection mechanism as in Mode 2(a), our proposed method includes complementary sensed information in the transmission by each transmitting node. This solution demonstrates significant improvement in the performance in terms of Packet Reception Ratio (PRR).

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