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Towards 6G-V2X Sidelink: Non-Orthogonal Multiple Access in the Autonomous Mode

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***Abstract*—The cellular-vehicle-to-everything (C-V2X) sidelink technology, specified in the long term evolution (LTE) and further improved in the fifth generation (5G) new radio (NR) standards to facilitate direct data exchange between vehicles, will play a crucial role in revolutionizing transportation systems. However, the demand for very high reliability and ultra-low latency services especially challenges the sidelink resource allocation mechanism when performed by distributed vehicles, in the so-called autonomous mode. One of the major causes of performance degradation is the resource allocation mechanism, which was designed for orthogonal multiple access (OMA) and can generate interference and collisions under high load conditions. In this context, here we argue in favour of the use of non-orthogonal multiple access (NOMA) as a game changer for sidelink in the upcoming sixth generation (6G)-V2X and the purpose of this paper is to provide a reference for further intriguing studies in the field. Additionally, the gain achievable over conventional allocation schemes by enabling NOMA through the use of successive interference cancellation (SIC) at the receiver is measured, through realistic simulations conducted when considering the latest C-V2X specifications.**

***Index Terms*—Automated and connected vehicles, vehicle-to-everything, sidelink, 6G, non-orthogonal multiple access, successive interference cancellation.**

I. INTRODUCTION

The automotive and transportation sectors are the key areas which demonstrate the breakthroughs of the fifth generation (5G) new radio (NR) communication system. In such a context, providing 5G connectivity over the *sidelink* of a vehicular user equipment (VUE), such as a car or a truck, is a pivotal enabler of a plethora of applications targeting cooperative automated driving (CAD). Unlike the conventional uplink/dowlink, the sidelink interface supports direct short-range vehicle-to-everything (V2X) communications between vehicles, or between vehicles and pedestrians, roadside units, and other stationary or moving road elements in the vehicle surroundings.

Sidelink communication has been one of the main focuses of the latest efforts of the Third Generation Partnership Project (3GPP) aimed at enhancing the cellular system with V2X connectivity support, under the umbrella term of cellular-V2X (C-V2X). Studies started from Release 14 with the long term evolution (LTE)-V2X technology. The recent NR-V2X sidelink specifications in Release 16 and the enhancements in Release 17 represent a step forward, but still cannot fully match the challenging reliability and latency requirements of CAD applications.

Sidelink communication is aimed at avoiding interference among simultaneously transmitting vehicles by selecting non-overlapping resources, based on an orthogonal multiple access (OMA) to the channel. Due to imperfect channel sensing and vehicle coordination, resource orthogonality cannot be always assured. This is especially true when the sidelink resources are selected by vehicles without the support of the base station (BS), in the so called autonomous mode (a.k.a. Mode 4 in LTE-V2X and Mode 2 in NR-V2X [1]). The limitations of half-duplex (HD) transceivers on board, vehicle mobility and hidden terminal phenomena can cause resource collisions leading to system performance limited by interference. The situation becomes worse as the number of transmitting VUEs or the channel load increases. Such a scenario is expected in the near future with the higher penetration rate of the C-V2X technology and because of bandwidth-hungry and information-rich CAD applications, e.g., cooperative sensing and manoeuvring [1]. Solutions targeting straightforward enhancements may not be sufficient to address the above scalability and capacity demands, and more disruptive techniques are required.

A possible game changer for future sixth generation (6G) V2X systems can be represented by non-orthogonal multiple access (NOMA) [2]. Unlike conventional techniques, NOMA, which is in general enabled by multiuser detection (MUD) and, more specifically, by successive interference cancellation (SIC) or parallel interference cancellation (PIC), allows multiple users to utilize overlapping time and frequency resources concurrently.

NOMA has been extensively studied for 5G downlink and uplink, with specifications introduced for the LTE downlink in Release 14 and a study conducted within the 3GPP for the 5G uplink in Release 16 [2]. However, its adoption to the more challenging C-V2X sidelink interface has not yet been discussed in standardization and it has only recently been considered in early literature works [3]–[12], with a few of them addressing the autonomous mode [6]–[8].

In order to fill this gap, the objective of this paper is to provide a general but concise view of what could be denoted as NOMA solutions, and discuss their implications and potential for the specific scenario of C-V2X sidelink, exhibiting peculiar features. NOMA is indeed not a single but a number of different techniques; it can be realized in the power-domain or code-domain, grant-based or grant-free, single or multi-slot, and also in a cooperative manner. Such techniques can be differently shaped in the V2X context and may all contribute to the evolution of sidelink towards a more robust, efficient and reliable 6G air interface. Towards this aim, we provide a review of the latest research works and, additionally, we show through original simulations conducted in realistic large-scale scenarios the significant improvement achieved just by the application of the main NOMA enabler, i.e., SIC, on top of the legacy C-V2X sidelink autonomous mode operation.

II. CELLULAR-VEHICLE-TO-EVERYTHING SIDELINK

Besides enabling communications over the conventional Uu interface in the uplink and downlink directions (between VUEs and BSs), the 3GPP C-V2X specifications allow direct communications among VUEs to occur over the sidelink interface, called PC5. Initially conceived in LTE-V2X to deliver, in broadcast, periodically generated traffic supporting basic safety applications, the sidelink has been revised by the latest NR-V2X specifications (considered in this paper) to satisfy the stricter reliability and latency demands of enhanced safety applications [1].

NR-V2X incorporates the new numerology and adds unicast/groupcast as optional transmission modes to deal with heavier data load, aperiodic traffic and larger packets.

NR-V2X sidelink channels up to 100 and 400 MHz can be allocated in the below 6 GHz and millimeter-wave spectrum, respectively. In practice, sidelink channels are currently allocated in the intelligent transport system (ITS) unlicensed band, which is reserved in several countries around 5.9 GHz.

A. The NR-V2X autonomous mode in a nutshell

In the *autonomous* mode, the VUEs select sidelink resources in a completely distributed manner. Such a mode is of crucial importance because it works in and out-of-coverage scenarios (e.g., tunnels, urban canyons) and allows safety-critical CAD applications to be leveraged in all situations.

The autonomous mode relies on a sensing-based semi-persistent scheduling (SB-SPS), according to which VUEs select the resources periodically for a given duration, after a channel sensing procedure[1]. In particular, the selection of time and frequency slots to accommodate a new data message transmission is decided based on the data delay budget and on the most recently monitored status of sidelink resources. During the so-called *sensing interval*, each VUE compares the received power, referred to as reference signal received power (RSRP), with a given threshold, and attempts to decode the transmitted sidelink control information (SCI), which carries scheduling information for the associated message. Resources not monitored or reserved by a prior SCI with an associated RSRP above the threshold are excluded from the pool of candidate resources for the current message. Time and frequency allocation is then issued among the remaining resources. The selected resource is then periodically reserved for a given interval, corresponding to a reselection counter. When the counter reaches zero, the resource is probabilistically changed.

The process was designed for periodic traffic but it is also used with aperiodic traffic. In the latter case, resource reservation for successive messages is not implemented, and the resource is released immediately after the transmission of every message. If all the VUEs generate aperiodic traffic without retransmissions, the sensing process cannot rely on any information and the selection is performed randomly.

B. Issues and future developments of the autonomous mode

In principle, the autonomous mode has been designed to allow an efficient and effective sharing of the (limited) radio resources, trying to prevent *a priori* collisions between different VUEs through the selection of non overlapping resources. In practice, the distributed nature of the algorithm coupled with the dynamic vehicular environment may unavoidably lead to performance degradation due to collisions and interference. First, HD VUE transceivers are not able to simultaneously sense the channel and transmit, which implies that the sensing procedure may not be fully accurate. Second, reciprocally hidden VUEs do not hear each other and may select overlapping resources. The resulting collisions, once occurring, may be persistent because VUEs may keep the overlapping resources for long time due to the semi-persistent allocation.

All these issues together make the OMA-based resource allocation algorithm, although well engineered, quite far from being interference-free and is not able to provide full reliability for the data exchanges required by future CAD applications. This is especially true as the channel load increases and transmitter-receiver distances become larger. Moreover, interference can be even more detrimental when aperiodic traffic is exchanged because both sensing and reservation of resources fail. Although the tuning of several algorithm's parameters can be tackled to improve the performance, such an approach is not sufficient [1], and alternative solutions can be explored to cope with the generated interference.

III. PECULIAR ASPECTS FOR NOMA IN C-V2X SIDELINK

Allowing users to interfere on the same resources, NOMA can improve spectral efficiency, reliability, and throughput while offering higher capacity. As an example, Fig. 1 shows a scenario where V2X communication is performed with the receivers improved by SIC; specifically, signals are concurrently broadcast by two VUEs (UE1 and UE2) and both correctly decoded by a third VUE (UE3) thanks to SIC.

The necessary counterpart is to endow the communication system with interference mitigation/cancellation capabilities, which imply extra computational complexity and processing time at the communication devices. In some cases, interference reduction is performed at the transmitter side using advanced

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[1] NR-V2X introduces quite a few changes into the SB-SPS used by LTE-V2X Mode 4. The reader can refer to [13] for more details.

TABLE I
NOMA TECHNIQUES: A TAXONOMY AND THEIR RELEVANCE IN C-V2X SIDELINK.

Technique	Principle and main characteristics	Specific aspects and relevance in C-V2X sidelink
Power-domain	Users multiplexed in power; optimized power levels to ensure successful SIC; highest power levels to the farthest users in downlink, the opposite in uplink; requires accurate CSI.	Challenging to acquire real-time CSI at the transmitter in highly dynamic vehicular environments and costly in terms of signalling overhead; difficult to implement power control in decentralized broadcast or groupcast due to cross interference brought to receivers in the overlapping regions of multiple transmitters' communication range.
Code-domain	Users multiplexed in code; different codes from properly designed codebook, assigned to different users.	Code selection performed autonomously by VUEs in highly dynamic scenarios.
Grant-based	The resources to be used, as well as power levels or codes, are specified by a central entity.	Can be used in the controlled mode or when vehicles are organized in groups with a leader; costly in terms of signalling overhead; risk of excessive access latency due to high mobility and possibly high density of devices.
Grant-free	Grant acquisition phase skipped; reduced access latency and signalling overhead at the expense of higher receiver complexity; enabling technique for mURLLC.	Relevant whenever full coverage from infrastructure cannot be guaranteed; complexity of receivers may not be an issue for the processing capabilities of VUEs.
Multi-slot	Transmission of multiple replicas of the same packet in different time-frequency slots; SIC to improve reliability.	Higher reliability at the expenses of higher system load; limitations due to half duplexing; need to accommodate the tight delay constraints, e.g., by adopting a specific frame structure, and to cope with fast changing channel conditions.
Cooperative	Messages relayed to improve coverage or reliability.	Larger communication range for specific applications.

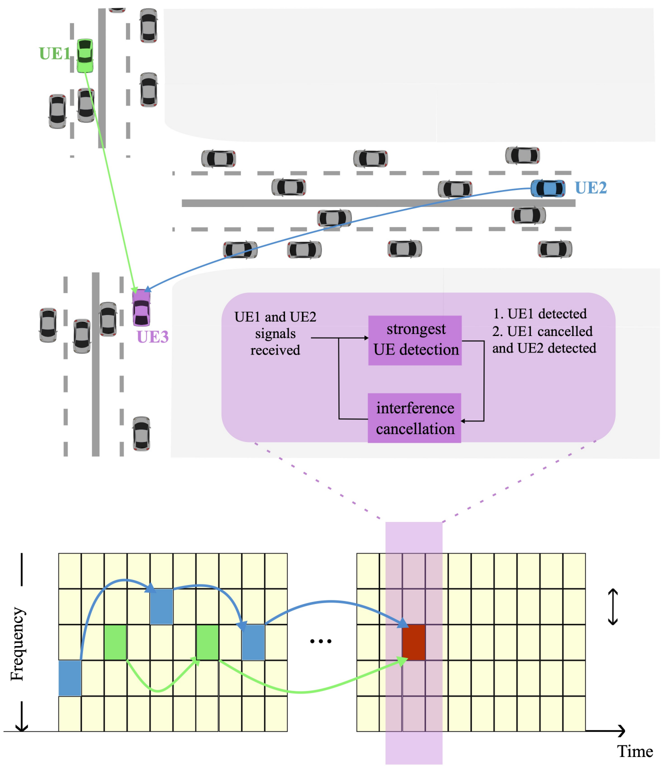

Fig. 1. SIC applied over sidelink Mode 2 at an intersection. In a given time-slot, vehicles UE1 and UE2 transmit concurrently (e.g., the sensing procedure failed because they are hidden to each other) towards vehicle UE3. By applying SIC, vehicle U3 is able to successfully decode both the signals.

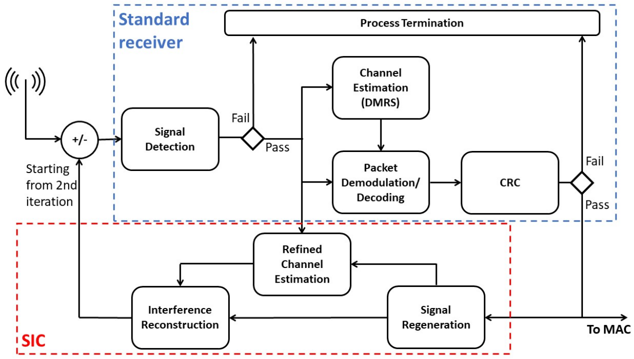

Fig. 2. Block scheme of the SIC-aided receiver. The standard receiver chain is shown in the blue rectangle and the SIC part in the red rectangle.

signal processing algorithms, such as optimized power allocation, beamforming, precoding, etc. In other cases, interference reduction takes place at the receiver side by using MUD, ranging from simple (suboptimal) linear detectors to advanced (optimal or near-optimal) nonlinear receivers able to perform joint channel estimation, MUD and channel decoding successively (SIC) or in parallel (PIC). A crucial aspect in the SIC or PIC-aided receiver is channel estimation, which normally requires a specific design of the reference symbols. A different design compared to OMA would be preferred, but may not always be necessary. For example, when SIC is applied to iteratively decode a single user's signal at a time, as illustrated in Fig. 2. The receiver first decodes the strongest signal (blue rectangle) just like for conventional OMA sidelink, and then it uses the entire reconstructed signal (i.e., pilot symbols and decoded data symbols) to perform fine channel estimation (red rectangle) before interference cancellation. These aspects need further studies.

While NOMA has been comprehensively investigated for infrastructured-based uplink and downlink communications, the sidelink application has only recently been considered. When investigating NOMA for C-V2X sidelink, the peculiarities of such an interface should be considered.

First, the ad-hoc-nature of the C-V2X sidelink and the high mobility of the nodes imply the need to constantly adapt to sudden variations of density, speed and propagation conditions.

The high mobility makes channel estimation more difficult and demanding in terms of dedicated resources (pilots and signal processing) and it must be taken into account that only partial and possibly inaccurate knowledge of the channel can be expected or assumed.

Second, the higher computational complexity required for NOMA is not an issue in the vehicular context, as the additional energy consumption for signal and data processing is substantially lower than the energy consumption dedicated to the driving system.

Third, more powerful chips including interference cancellation can be employed on board the VUEs without increasing the total cost of the vehicles too much.

Fourth, whereas a large part of the literature addressing NOMA focuses on unicast transmission, special attention is deserved by broadcast and groupcast transmissions, which are the most prominent options for data exchange amongst densely co-located vehicles for the purpose of context awareness, collective perception or coordinated manoeuvres.

Finally, the tight latency constraints in safety-critical applications make the design of C-V2X NOMA schemes more challenging than in other communication scenarios. While additional processing delay introduced by the SIC or PIC appears negligible with current interference cancellation technologies, this aspect deserves to be studied in detail to understand *(i)* how defining the number of iterations as a function of the latency requirements and *(ii)* if the process is also feasible in smaller, battery-limited, and cheaper vehicular devices.

IV. NOMA TECHNIQUES: A TAXONOMY AND THEIR RELEVANCE IN C-V2X SIDELINK

As mentioned, NOMA is a general term for several different techniques. In this section, we review the various principles that differ in terms of domain for signal superposition (power or code), type of allocation (grant-based or grant-free), number of transmissions (single or with replicas), number of hops (single hop or multiple hops), and comment on their relevance for C-V2X sidelink. The main points, related literature and peculiar aspects are reported in Table I and Table II.

A. Power-domain vs. code-domain NOMA

NOMA can be implemented in the power domain, the code domain, or a combination of these.

1) Power-domain NOMA: Users' multiplexing is performed in power domain, i.e., users' signals are superimposed in the same time/frequency resources at different power levels, and SIC is employed at the receiver. The receiver detects and decodes the stronger signals to improve the probability of decoding the weaker ones. The basic idea is to control the transmission power so that there is a received power difference, which makes the power allocation strategy critical. Normally, in the downlink of conventional cellular systems, more power is given to users with smaller downlink channel gains, which are also those whose signals are decoded and subtracted first. In the uplink, the power allocation strategy is assumed to be tightly controlled by the BS through feedback and obeys the water-filling policy: users with higher channel gains are allowed to transmit with more power, then their signals are decoded and subtracted first.

Relevance for C-V2X sidelink. Power-domain NOMA has been recently considered in a few works addressing C-V2X sidelink. In [3] the authors analyse power-domain NOMA from the physical (PHY) layer perspective, without paying attention to vehicle distributions and medium access control (MAC) layer aspects. Concurrent transmissions are assumed in an ideal scenario and the performance is evaluated at the possible receivers aided with SIC or PIC capability. Both receivers are shown to offer significant improvements compared to the conventional OMA approaches, with PIC providing significantly better performance only for the case of highly loaded system and few receive antennas. The resource allocation is instead taken into account in [4]–[9]. A centralized resource allocation mechanism based on kinematic information is proposed in [4], without exploiting channel state information (CSI). In a controlled highway scenario and assuming an ideal SIC, results show a performance close to an interference-free situation. A mixed centralized/distributed power-domain NOMA strategy is instead proposed in [5] to solve the issue of inaccurate CSI in highly-dynamic vehicular environments. The BS performs centralized spectrum management using SB-SPS based on global position information and partial CSI (i.e., restricted to path loss and shadowing), while the VUEs perform dynamic distributed power control in each time slot. Simulations demonstrate that the proposed scheme, which requires the introduction of additional control signalling in the sidelink, outperforms the conventional one both in terms of reliability and latency. A distributed resource allocation algorithm is considered in [6]–[8], where the LTE Mode 4 is enhanced thanks to ideal SIC. In [6], this algorithm is referred to as SPS-NOMA and ideal SIC is used to resolve signals from different sources. In [7] and [8], each vehicle exploits the NOMA capability to concurrently send two messages, where one is sent with a low power level and received, by the nearest neighbours, after cancellation of the other. In [7], the algorithm is used for new content transmission and in [8] to relay data previously received. The relaying exploiting power-domain NOMA is also proposed in [9], adopting the controlled mode. In all the cases, an important aspect is the setting of the power level. Whereas in the controlled mode, the indication can be provided by the BS as in [4], in the autonomous mode each station may act depending on the local knowledge or based on additional exchanges, as in [5], at the cost of high redundancy. The optimal setting of the power levels for more packets concurrently transmitted is deepened in [8] and [9]. In the other studies, where broadcast transmissions of a single packet is considered, constant power is assumed. This appears reasonable given that there are several receivers at different distances, and that the number of channels to be monitored and reported quickly increases with the density. However, it is not clearly proved that power-controlled NOMA is ineffective in such case and is left as an open point.

2) Code-domain NOMA: Users' multiplexing is performed in code domain, i.e., users are superimposed in the same time/frequency resources with the aid of user-specific signatures or spreading codes.

Relevance for C-V2X sidelink. Code-domain NOMA has been considered mainly for the cellular uplink, due to the lower required signalling, rather than for the downlink. For the same reason, it might be relevant also for C-V2X sidelink and has been actually considered in a few early works, e.g., [10], [11]. In [10], well-designed transmit signatures, combined with an advanced SIC receiver are used to resolve collisions. In [11], a simplified platooning scenario is assumed, with VUEs, spaced 50 m apart, acting as multicast decode-and-forward relays.

B. Grant-based vs. grant-free NOMA

In infrastructure-based networks, the access to the channel is generally controlled by a *grant-based* scheduling mechanism through a four-way handshake procedure. Grant-based NOMA ensures that the level of interference to be processed at the receiver remains below an acceptable threshold, at the expense of large access latency and signalling overhead. On the other hand, massive sporadic connectivity in the context of massive machine-type communications and faster connectivity in the context of ultra-reliable and ultra-low latency communications (URLLC) have raised interest for *grant-free* random access, inherently NOMA, where the grant acquisition phase prior to transmission is skipped [14]. While grant-free NOMA reduces access latency and signalling overhead, it also complicates the task of the receiver, which does not know the instantaneous system load and must perform user activity detection and channel estimation prior to (or jointly with) MUD and decoding.
Relevance for C-V2X sidelink. When NOMA is associated to the autonomous mode of C-V2X sidelink, it is inherently grant-free, unless vehicles are organized in groups, such as for platooning, and elect a leader to control the allocation [1]. It can be either power-domain grant-free, as in [6], or code-domain grant-free, as in [10].

C. Multi-slot NOMA

Conventional use of the resources assumes that one transmission is scheduled in one resource. Another option is the use of *multi-slot* for the transmission of replicas of the same packet. Although it brings to blind retransmissions and maximum ratio combining (MRC)-based reception when applied to OMA, it opens new possibilities in NOMA. Indeed, when one of the replicas of a given packet is correctly decoded in a given slot, the contribution of this packet can be subtracted through SIC in any other slot where it is repeated, enabling other packets to be correctly decoded in their turn, and so on.
Relevance for C-V2X sidelink. In C-V2X sidelink, the extraordinary potentiality of multi-slot NOMA collides with the higher complexity caused by the very variable scenarios in terms of density and speed, and with the strict delay budget limitations. Other issues that are likely to represent a challenge, especially in vehicular environments, are the packet overhead that contains the pointers to keep track of where the replicas are allocated and the perfect synchronization required. Indeed, only a preliminary investigation applied to the vehicular scenario is presented in [12], where broadcast transmissions are assumed. The authors focus on a very simplified scenario and show that the proposed protocol significantly outperforms other schemes for medium to high channel loads. Results also suggest that the number of repetitions needs to be carefully set, otherwise the higher channel congestion and HD limitations may be unacceptable.

TABLE II
OVERVIEW OF LITERATURE WORKS ABOUT NOMA FOR V2X SIDELINK (BC=BROADCAST, UC=UNICAST, GC=GROUPCAST).

Year,Ref.	**Focus**	**Cast**	**Dom.**	**Grant**	**Slots**
2020 [3]	Performance of SIC/PIC receivers	BC	Power	n.a.	Single
2018 [4]	Mode 3 with SIC	BC	Power	Based	Single
2017 [5]	Mixed centralized-autonomous	BC	Power	Based	Single
2020 [6]	Mode 4 with SIC & 2 SB-SPS processes	BC	Power	Free	Single
2020 [7]	Mode 4 with multiple packets together	BC	Power	Free	Single
2021 [8]	Mode 4, NOMA-based tx+relay	BC	Power	Free	Single
2019 [9]	Mode 3, NOMA-based tx+relay	BC	Power	Based	Single
2021 [10]	PHY layer of uncoordinated NOMA	BC	Code	Free	Single
2020 [11]	Sparse-code multiple access for relaying inside a platoon	UC, GC	Code	Based	Single
2017 [12]	Multi-slot NOMA in simplified scenario	BC	Power	Free	Multi

D. Cooperative NOMA

In cellular networks, cell-edge nodes experiencing weak received signal power may greatly benefit from cooperative NOMA. The idea is to use nodes with better channel conditions as relays. Cooperative node selection, clustering strategies and relaying protocols represent possible variations of the concept.
Relevance for C-V2X sidelink. Cooperative NOMA appears for future extensions of C-V2X sidelink beyond single-hop transmissions. The work in [11] is an example of cooperative NOMA based on code-domain. In [8] and [9], cooperative schemes are presented for broadcast transmissions, where each VUE jointly transmits its message and relays one of those received, adopting power-domain NOMA.

V. EVALUATION STUDY

The complexity and cost of NOMA may not be negligible, and sufficient improvement needs to be demonstrated to motivate its use in future C-V2X sidelink. To this aim, results beyond the state-of-the-art are shown here, focusing on a first evolutionary step, where SIC is added to the autonomous resource allocation *(i)* on top of the latest NR-V2X specifications, and *(ii)* assuming imperfect SIC. Results are presented for both Mode 2 and random access schemes. Whereas the former is designed for periodic traffic to limit the level of interference *a priori*, the latter is the simplest possible resource allocation scheme, actually performed in NR-V2X in the absence of channel sensing information. It is worth noting that neither Mode 2 nor random access can offer guarantees that the user's signals do not collide. When SIC is added to these schemes, the intention is to tolerate some interference and treat it at the receiver, which is the core of NOMA.

A. SIC modeling

The SIC algorithm implemented in the open-source WiLabV2Xsim simulator [13] proceeds as follows. The receiver first attempts to decode the strongest user's signal (by the capture effect). If it succeeds, it removes its contribution from the received signal, and then attempts to decode the second strongest user's signal, and so on. The process is then iterated, until no signal can be decoded. We consider two cases: ideal SIC and non-ideal SIC. Non-ideal SIC means that only part of the user's signal is removed or, equivalently, that residual interference remains. Residual interference might result from imperfect users' channel estimation, approximate (hard or soft) estimation of users' modulation symbols, etc. As a first approximation, we model it as additive noise with zero mean and variance given by the received power minus the so-called SIC capability expressed in dB (such as, e.g., in [15]).

B. Simulation settings and evaluation metrics

Simulation settings and evaluation metrics are closely aligned to 3GPP specifications [1]. In particular, results are derived in a dense highway with 100 to 500 vehicles/km moving over 3+3 lanes on average at 70 km/h and transmitting in broadcast 1000 bytes-long packets, generated every 100 ms. A bandwidth of 20 MHz and 1 ms-long slots are assumed, with 23 dBm transmission power. The antenna gain at both transmitter and receiver is set to 3 dBi and the noise figure at the receiver is set to 9 dB. The WINNER+ B1 model for the path loss and correlated log-normal large-scale fading, with shadowing standard deviation of 3 dB and decorrelation distance of 25 m, are considered. All VUEs use QPSK with a coding rate of 0.37, corresponding to the most reliable modulation and coding scheme (MCS) to transmit 1000 bytes in 20 MHz and 1 ms [13]. The results are provided in terms of:

- packet reception ratio (PRR), corresponding to the ratio of correct receptions by the VUEs at a given distance from the transmitter.
- packet inter-reception (PIR), derived as the time elapsed between two consecutive successful receptions by a VUE from the same VUE located within 300 m.

The PRR measures reliability, whereas the PIR metric captures the probability of bursts of errors. Therefore, the PIR metric is more relevant for high values, which imply that a vehicle does not receive any updates by another vehicle in its proximity for a long time, potentially causing a threat for road safety.

C. Simulation results

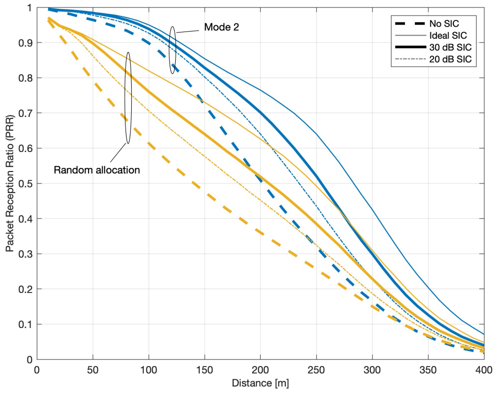

Fig. 3. PRR vs. distance (200 vehicles/km).

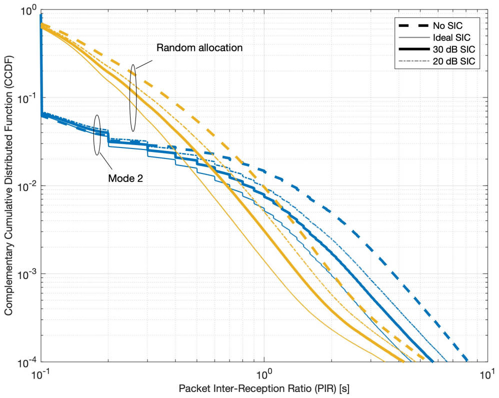

Fig. 4. CCDF of PIR (200 vehicles/km).

In Fig. 3, the PRR is shown versus the transmitter-receiver distance, with 200 vehicles/km. Thanks to the SB-SPS mechanism, Mode 2 limits the interference *a priori* and significantly outperforms the random allocation. Indeed, by examining the cases without SIC (dashed lines) and comparing the maximum distance to have a PRR above 0.9, which is a common value for these studies, Mode 2 achieves almost four times the distance achieved with random allocation. Also, it is clearly appreciable the improvement obtained with SIC. If we again examine the maximum distance to have the PRR above 0.9, it can be observed that the ideal SIC in Mode 2 allows more than 30% improvement and in the random allocation it allows more than 100% improvement. Remarkably, the PRR increase is also achievable with non-ideal SIC, with 20 to 30 dB SIC capability [15].

The improvement is higher with the random allocation, which may be of particular relevance when the transmitters cannot perform continuous sensing, such as those of vulnerable road users, or when the traffic is not periodic. In fact, still looking at the maximum distance to have a PRR above 0.9, the gap in performance between random and Mode 2 approximately reduces from 4× to 2.5× in the presence of SIC. This is because the blind resource selection in random access creates more interference and thus, benefits more from SIC than Mode 2.

The same cases are analysed in Fig. 4 in terms of the complementary cumulative distribution function (CCDF) of PIR. As observable, SIC provides a clear improvement also looking at this metric. Focusing, for example, on a CCDF of 10^{-3} and Mode 2, the PIR halves from 3.5 s with no SIC to

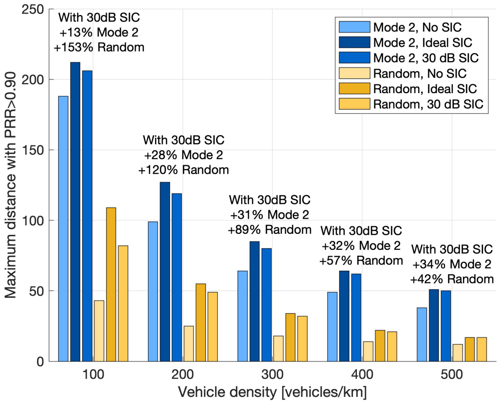

Fig. 5. Maximum distance to have PRR>0.9.

less than 2 s with ideal SIC. Relevantly, the random allocation is preferable compared to Mode 2 from the point of view of PIR if we look at values of the PIR above 1 s, meaning that the random allocation reduces the probability of long bursts of errors.

Finally, in Fig. 5, the maximum distance to have PRR above 0.9 is shown, when varying the vehicle density and consequently the channel occupation. As observable, the gain using SIC is large and, remarkably, the difference between ideal and non-ideal SIC remains small, especially with increased channel use.

VI. CONCLUSIVE REMARKS AND FUTURE PERSPECTIVES

In this work, we discussed the opportunities that NOMA may bring for the next generation of C-V2X sidelink, by discussing the possible directions, with their potential advantages and challenges. In addition, results assuming the autonomous mode of NR-V2X sidelink aided with SIC-based NOMA show a significant improvement both in terms of higher reliability and lower probability to have long bursts of errors, even when SIC is not ideal.

Overall, these encouraging outcomes pave the way for pushing NOMA into the autonomous C-V2X sidelink and contributing to the evolution of V2X towards 6G.

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