5G NR V2X: On the Impact of a Flexible Numerology on the Autonomous Sidelink Mode

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Abstract—The Cellular Vehicle-to-Everything (C-V2X) radio access technology has been specified by the Third Generation Partnership Project (3GPP) in Releases 14 and 15, with special focus on enabling direct communication between vehicles, over the sidelink PC5 interface. More recently, 3GPP has launched the New Radio (NR) standardization activity for the first phase of fifth generation (5G) systems and is ready to enhance C-V2X in several ways under the 5G NR Release 16. 5G NR V2X will encompass flexible numerologies and agile frame structure, higher frequency spectrum, novel and more sophisticated multiple access techniques that well answer the quest for high capacity, ultra-low latency and high reliability of the cooperative automated driving use cases. In this paper, we investigate the impact of the NR flexible numerology, i.e., scalable Transmission Time Interval (TTI) duration and sub-carrier spacing (SCS), on the C-V2X autonomous access mode, according to which vehicles self-allocate resources for transmission. Whereas it is well known that shorter TTI and larger SCS facilitate latency reduction, they have also the potential to mitigate the interference generated in the frequency domain. Achieved simulation results show that the investigated NR features provide several improvements in terms of message reliability and timeliness when compared to the legacy C-V2X solution.

Index Terms—Vehicle-to-Everything, 3GPP, 5G New Radio, TTI, sub-carrier spacing

I. INTRODUCTION

Connected and fully automated vehicles will contribute to road safety aiming at zero fatalities on the road, improved traffic flow, and consequent low environmental impact. To achieve such ambitious objectives, vehicle-to-everything (V2X) communications should ensure ultra-low latency and high reliability, well beyond what the current radio access technologies are able to provide today.

There is a general consensus among the stakeholders about the crucial role of the fifth generation (5G) systems to realize such a challenging vision. The Third Generation Partnership Project (3GPP), after issuing the specifications for Long Term Evolution (LTE)-V2X (LTE-V2X) in Releases 14 and 15, is currently discussing further enhancements for Release 16, in order to meet the most demanding V2X performance requirements in alignment with the 5G New Radio (NR) specifications. 3GPP has adopted cellular-V2X (C-V2X) as a general term covering all release enhancements for V2X.

NR encompasses flexible numerologies and agile frame structure, the usage of mmWave bands, and advanced multiple access techniques [1]. The 5G NR-based C-V2X is expected to build upon such innovative features in order to provide sidelink communication via the PC5 interface for both basic V2X services [2], which rely on the periodic exchange of cooperative awareness messages (CAMs) [3], and advanced V2X use cases [4] entailing, for example, the prompt dissemination of vehicles’ planned maneuvers [5].

In C-V2X, CAMs are exchanged through the following access options. In Mode 3 (a.k.a. scheduled), resource allocation on the sidelink is orchestrated by the eNodeB. In Mode 4 (a.k.a. autonomous), instead, vehicular user equipments (VUEs) access a set of pre-configured radio resources in a distributed manner, without the network coordination. More in detail, VUEs self-allocate the resources which are monitored and sensed as either idle or weakly interfered.

Due to the lack of perfect coordination, exacerbated by the vehicle mobility, the autonomous resource selection may cause two or more VUEs to interfere because they seize the same radio resources. Moreover, interference may also be experienced at the VUEs selecting adjacent radio resources in the same subframe, due to the in-band emission (IBE), i.e., the power leakage from the allocated transmission bandwidth immediately outside the assigned channel bandwidth [6].

In this paper, we evaluate the performance of C-V2X Mode 4 augmented with the NR flexible numerology. Unlike the static sub-carrier spacing (SCS) used in LTE, resulting in a fixed 1 ms-long transmission time interval (TTI), NR supports scalable SCS settings, from 15 to 480 kHz, and a TTI duration down to 31.125 µs that facilitate latency reduction, which is an especially critical factor for advanced V2X use cases.

Specifically, the conducted study aims at unveiling if and to which extent the NR features of a shorter TTI and a larger SCS can affect the autonomous resource selection procedure devised for C-V2X Mode 4. Achieved simulation results show some reliability improvements that are mainly to be ascribed to the reduction of the IBE contributions when larger SCS and shorter TTI are used. Such findings are particularly interesting for the mid-term adoption of NR-based C-V2X as an enabler of basic V2X services.

The remainder of the paper is organized as follows. Section II provides an overview of the C-V2X specifications as frozen in Release 14, with a focus on Mode 4 physical (PHY) and medium access control (MAC) layer procedures. In Section III we analyze the main 5G NR-based C-V2X features,
with emphasis on the flexible numerology. Section IV reports
the results of a simulation campaign performed using the open-
source LTEV2Sim simulator [7]. The objective is to compare
the autonomous sidelink access with the legacy numerology
against the NR’s numerology solution, and get insights into
meaningful CAM performance metrics under a wide range of
settings. Section V summarizes conclusions and gives hints
for future work.

II. C-V2X: AN OVERVIEW

Since the publication of the first part of Release 14, in
September 2016, 3GPP has witnessed the automotive vertical
gaining interest from the cellular ecosystem, thus coining the
acronym C-V2X. Besides the introduction of new architecture
components to manage the V2X scenario with legacy vehicle-
to-infrastructure (V2I) connections over the conventional LTE-
Uu interface, particular emphasis was placed on short-range
vehicle-to-vehicle (V2V) and vehicle-to-roadside (V2R) com-
munications on the sidelink (opposed to uplink and downlink)
over the new PC5 interface. Starting from the work done
for device-to-device (D2D) communications in public safety
applications, changes to the signal structure were introduced
and specific procedures were defined for the allocation of V2X
radio resources.

A. C-V2X: the sidelink PHY and MAC layers

The C-V2X sidelink shares the same single carrier-
frequency division multiple access (SC-FDMA) technique as
the LTE uplink, with the same time structure and the same
numerology. In the time domain, the minimum resource is
the TTI (or subframe) of 1 ms, which corresponds to 14
multi-carrier symbols. In the frequency domain, a group of 12
subcarriers spaced 15 kHz apart form a resource block (RB)
of 180 kHz.

Unlike the long-range LTE, in the time domain only 9 sym-
bols (instead of 12) are used for data transmission, since those
dedicated to the demodulation reference signals (DMRSs) have
increased from 2 to 4, with the last symbol left empty to allow
timing adjustment and transmission-to-reception switching. In
the frequency domain, the concept of subchannel has been
included that groups a given number of RBs, and has become
the granularity for resource allocation. Every data packet may
occupy one or more adjacent subchannels during one TTI. For
each packet, the control part, which is transmitted within the
the so-called sidelink control information (SCI), is carried on
dedicated resources in the same TTI.

The main traffic pattern considered for the C-V2X sidelink
is the periodic transmission of messages called CAMs by
ETSI [3], which are sent in broadcast by all vehicles to
advertise their position and movements. Given the periodicity
of these packets, the allocation can be performed with a semi-
persistent scheduling (SPS) approach: a given portion of time
and frequency is chosen and, then, used periodically, without
further decision making, for a certain time interval. The choice
of the resources to be used and the moments in which to carry
out a reallocation can be established either by the network or
autonomously by each vehicle. The former procedure is called
Mode 3 and requires network coverage to be applicable; no
specific algorithm is detailed by 3GPP in that case and is left
to the operator. The latter is known as Mode 4 and deserves
special attention for the following motivations. First, it is the
only option working in out-of-coverage conditions (e.g., urban
canvons, tunnels). Second, it avoids heavy control load over
the LTE-Uu interface. Finally, it overcomes complications due
to handover between cells and between networks belonging to
different operators.

In the rest of this paper, we will focus on Mode 4 and for
this reason we dedicate the following subsection to summarize
its operations. The interested reader can find a more detailed
description for example in [8], [9].

B. Mode 4: the autonomous sidelink access

In [10], [11], 3GPP defines a standard SPS algorithm for
selecting and using the resources to be allocated to CAMs.
It is based on a sensing procedure and operates at both PHY
and MAC layers. At PHY layer, a vehicle continuously senses
the radio channel and averages the received signal strength
values in the last second. These measurements are used, when
commanded by the MAC layer, to select the 20% of the
resources that have been least interfered and, therefore, are
less prone to collisions.

At the MAC layer, the selected resources are maintained
for a uniformly distributed random period, lasting between
0.5 s and 1.5 s for CAMs transmitted every 100 ms. Then, the
resources are changed with probability $1-p_k$; with probability
$p_k$, instead, they are kept for another random interval, again
selected within a given range, and so on.

C. Relevant issues

What is worth highlighting for the purposes of this paper is
that 4G and (in all likelihood) 5G devices have the constraint
of half duplexing. This means that the sensing procedure
cannot be performed while the device is transmitting, and that
messages sent by neighboring vehicles during the same TTI
cannot be received, although they are using different RBs.

In addition, the orthogonality in the frequency domain is
not ideal. Therefore, the interference due to IBE is always
present among transmissions performed during the same TTI,
even if they use nominally orthogonal resources. Emissions
in adjacent resources result from the modulation process and
non-linearity in the transmitter [6]. Such issues motivate the
exploration of possible improvements to the legacy procedures
envisioned by 3GPP specifications.

D. Literature overview

Due to the infancy of the topic, works in the literature
mainly focused on understanding the impact of the main
PHY/MAC parameters and tuning them properly [9], [12],
[13]. For instance, the parameter $p_k$, statically set by the
network, is shown to strongly affect the trade-off between
reliability and latency in [9], [13]. In [14] we proposed to
dynamically adapt such a parameter according to the status
of selected resources, monitored through the sensing-while-transmitting capability of a full-duplex transceiver. The proposal enhances the sensing-based SPS approach by letting a VUE detect collisions while transmitting and, consequently, make a more informed decision about keeping or changing the resources, once the reservation phase is expired.

Instead of leveraging system-level simulations, in [15] analytical models have been derived to characterize different types of transmission errors in Mode 4, such as errors due to propagation loss, packet collisions, and half-duplex operation.

The aforementioned literature proposes slight enhancements to the sensing-based SPS algorithm of C-V2X but most analysed parameter settings are still calibrated over the LTE’s figures. This work intends to make a step forward in that it investigates the impact of a specific NR feature, i.e., the flexible numerology.

III. TOWARDS 5G NR V2X

In March 2019 the 3GPP approved a work item for the inclusion of the first specifications of 5G NR-based C-V2X in Release 16 in the first half of 2020. NR C-V2X encompasses many enhancements to the current C-V2X specifications for both the LTE-Uu and the PC5 interfaces [16]. For what concerns the PC5, the main envisioned modifications can be grouped as follows:

- The communication scope is extended to unicast and groupcast, besides broadcast that was the focus of C-V2X, to let a transmitting VUE target, respectively, a single receiver and a specific sub-set of VUEs in the surroundings.
- For the aforementioned types of communications, reliability can be improved through a sidelink feedback channel, which enables feedback-based retransmissions, instead of the blind ones allowed by C-V2X.
- The long-term sensing which characterizes Mode 4 can be replaced through a short-term sensing whenever aperiodic traffic needs to be exchanged in a promptly manner.
- Similar to C-V2X, 5G NR-based C-V2X will primarily use the 5.9 GHz band, which has been allocated worldwide for automotive use. In addition, frequencies above 6 GHz are expected to be exploited to accommodate bandwidth-hungry V2X applications.
- Contrarily to the fixed spacing between subcarriers used in C-V2X, NR C-V2X supports scalable SCS and TTI duration.
- Transmissions are no longer bounded to the subframe duration. NR C-V2X allows a VUE which has only a small amount of data to send, which can be accommodated in less than 14 orthogonal frequency division multiplexing (OFDM) symbols, to occupy only the required number of symbols, the so-called mini-slots.
- Whereas the first four modifications listed above are peculiar for V2X environments, the latter two are more general and are aligned with the NR features introduced from Release 15. In this paper, we focus only on the NR feature of scalable SCS and TTI, and we analyze the impact of a flexible numerology on the performance of V2X communications over the sidelink. The SCS, $\Delta f$, values depend on the numerology $\mu$, according to the following law: $\Delta f = 15 \cdot 2^\mu \text{kHz}$, hence scaling from 15 to 480 kHz, as reported in Table I. SCS of 15, 30 and 60 kHz will be supported at the 5.9 GHz spectrum, whereas higher values will be supported for frequency bands above 6 GHz.

The use of larger SCS facilitates latency reduction. In fact, assuming that each VUE requires one slot for its CAM transmission, the transmission duration decreases as the SCS increases. Furthermore, wider SCS enables better handling of Doppler shift and frequency offset. Due to the shorter slot duration, channel variations within the slot will be smaller, thereby needing fewer DMRS symbols per slot for channel estimation. Intersymbol interference (ISI) might appear as a consequence of having larger SCS. To avoid it, an extended cyclic prefix (CP) option exists in 5G NR which, in principle, reduces the OFDM efficiency. Such a penalty may be somehow compensated for by using less DMRS symbols per slot.

IV. PERFORMANCE EVALUATION

For the purpose of our study, a large simulation campaign has been conducted using LTEV2Vsim [7], an open source simulation tool developed in MATLAB. It focuses on the cooperative awareness service of connected vehicles and closely models the PHY and MAC layer protocols of sidelink C-V2X.

A. Simulation settings

The simulation parameters are set according to 3GPP specifications [9], as summarized in Table II. The CAM size is set equal to 300 bytes, a common value to capture the demands of many cooperative awareness applications [17]. Each VUE transmits a CAM at every $T_{\text{CAM}}$, which is a varying parameter in our simulations and is set to 50 and 100 ms to capture the periodic packet generation rate of many

### TABLE I

<table>
<thead>
<tr>
<th>$\mu$</th>
<th>$\Delta f$ (kHz)</th>
<th>Symbols per slot</th>
<th>TTI duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>15</td>
<td>14</td>
<td>1 ms</td>
</tr>
<tr>
<td>1</td>
<td>30</td>
<td>14</td>
<td>0.5 ms</td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>14</td>
<td>0.25 ms</td>
</tr>
<tr>
<td>3</td>
<td>120</td>
<td>14</td>
<td>0.125 ms</td>
</tr>
<tr>
<td>4</td>
<td>240</td>
<td>14</td>
<td>62.5 $\mu$s</td>
</tr>
<tr>
<td>5</td>
<td>480</td>
<td>14</td>
<td>31.25 $\mu$s</td>
</tr>
</tbody>
</table>

### TABLE II

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAM periodicity ($T_{\text{CAM}}$)</td>
<td>50 ms, 100 ms</td>
</tr>
<tr>
<td>CAM size</td>
<td>300 B</td>
</tr>
<tr>
<td>MCS</td>
<td>WINNER+, Scenario B1</td>
</tr>
<tr>
<td>Propagation model</td>
<td>7, 14</td>
</tr>
<tr>
<td>Transmission power</td>
<td>23 dBm</td>
</tr>
<tr>
<td>Noise figure</td>
<td>9 dB</td>
</tr>
<tr>
<td>Antenna gain (tx, rx)</td>
<td>3 dB</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>10, 20 MHz</td>
</tr>
<tr>
<td>SINR threshold</td>
<td>7.29 dB (MCS=7), 16.39 dB (MCS=14)</td>
</tr>
<tr>
<td>Resource keep probability $p_k$</td>
<td>0.8</td>
</tr>
</tbody>
</table>
We model a highway scenario, where vehicles – distributed across 6 lanes per direction – move at an average speed of 50 km/h. A varying average number of vehicles per kilometer (ρ = 100, 200, 300) has been generated using Poisson point processes, to resemble different density settings.

The following metrics are considered to assess the CAM reliability and timeliness, respectively.

- The packet reception ratio (PRR) is computed as the average ratio between the number of neighbours correctly decoding a CAM and the overall number of neighbours within a certain distance from the transmitter.
- The update delay (UD) is the average time difference between two consecutive successfully decoded CAMs from a given transmitter at a given receiver that is located within 150 m, which is referred to as awareness range and represents the distance within which the CAM is particularly relevant for the receiving VUEs.

1 The same thresholds are used for NR in order to focus on the impact of the new numerology, even if the addition of quasi-cyclic low-density parity-check (QC-LDPC) codes, used by 5G NR for channel coding, allows 0.5–1.0 dB lower SINR for the block error rates of interest.

2 Its setting is a design choice that may depend, for example, by the specific V2X application.
B. Simulation Results

The effects of different input parameters on the two compared schemes are discussed in the following.

Impact of vehicle density. Fig. 1(a) reports the PRR for both the legacy solution with TTI equal to 1 ms (SCS=15 kHz) and the NR solution with a TTI equal to 0.5 ms (SCS=30 kHz), when varying the VUE density. As expected, as the VUE density increases the PRR metric decreases. The NR scheme achieves better performances w.r.t. the legacy one. Such improvements have to be ascribed to the fact that when halving the TTI duration, the SCS gets doubled, hence a single CAM can be accommodated in a (shorter) TTI (instead of two in a 1ms-long TTI, for the legacy scheme). The main consequence is that the transmission of CAMs is not affected by IBE, for the considered settings. As the density increases, the impact of IBE gets stronger and the improvement due to the shorter TTI amplifies. The distance at which a PRR of e.g., 0.95 can be ensured passes from 85 m for the legacy case to 150 m in the NR-based approach for $\rho$ equal to 300. The increased communication range provides evident road-safety improvements, because a vehicle has higher chances to become aware of road conditions at a higher distance and, consequently, has more time to prepare and properly react to safety warnings. Moreover, the differences between the NR solution and the legacy one get higher as the transmitter-receiver distance increases.

For the same reasons, the NR scheme outperforms the legacy one also in terms of UD, as reported in Fig. 2(a). The Figure shows that for the majority of VUEs, consecutive CAMs are received within 100 ms, regardless of the considered scheme. Then, the probability of experiencing a UD above a given value is higher for the legacy scheme compared to the NR one, for all the considered density settings. In other words, longer bursts of errors, implying higher UD, are more likely to occur in the legacy scheme.

Impact of CAM frequency and bandwidth. The benefits of a shorter TTI duration are kept also when considering a higher CAM frequency, as shown in Fig. 1(b). The PRR unavoidably decreases when $T_{\text{CAM}}$ decreases, since the load is higher and, hence, the interference is more likely to occur. Interestingly, for $T_{\text{CAM}}$ equal to 100 ms, the NR-based solution occupying 10 MHz outperforms the legacy solution, also when its bandwidth is increased from 10 MHz to 20 MHz. Indeed, looking at the legacy cases, the larger bandwidth allows to better spread CAM transmissions, with 4 CAMs possibly transmitted in the same TTI. However, the IBE contribution still remains high and the shorter TTI of NR preferable.

The same conclusion does not fully hold for $T_{\text{CAM}}=50$ ms and differences between the NR scheme and the legacy one with 20 MHz get smaller in that case. When CAMs need to be transmitted more frequently, a higher number of RBs can be highly beneficial to reduce the interference. Furthermore, as the transmitter-receiver distance increases, the higher sensitivity to the noise for the larger SCS slightly penalizes the NR scheme. Remark anyway that these considerations are valid comparing NR at 10 MHz with the legacy counterpart at 20 MHz. Fig. 2(b) confirms the superiority of the NR scheme w.r.t. the legacy one also in terms of UD for the typical $T_{\text{CAM}}=100$ ms setting, under all the considered bandwidth values. For $T_{\text{CAM}}=50$ ms, improvements still exist w.r.t. the legacy scheme in the common 10 MHz bandwidth setting. Differences are less noticeable when NR is compared against the legacy solution with the channel bandwidth set to 20 MHz.

Impact of MCS. Fig. 1(c) reports the PRR when considering different MCS settings for the same CAM size, which results in a different number of CAMs that can be transmitted per TTI. In particular, we consider MCS 7 and 14. The legacy numerology allows to allocate 2 CAMs per TTI with MCS 7 and 4 CAMs per TTI with MCS 14. In the NR case, we scale the SCS in order to allocate a single CAM per TTI: with MCS 7, SCS becomes equal to 30 kHz and the TTI reduces to 0.5 ms, while with MCS 14, SCS increases to 60 kHz and the TTI further reduces to 0.25 ms.

For both MCS settings, the NR scheme outperforms the legacy one. The improvement is more remarkable for MCS=14 and $T_{\text{TTI}}=0.25$ ms. Indeed, in the latter case, in 1 ms, up to four CAMs can be transmitted by leveraging fully orthogonal resources, compared to the case of two CAMs for $T_{\text{TTI}}=0.5$ ms. At a transmitter-receiver distance of 100 m, the PRR passes from nearly 0.94 for the legacy case (for both considered MCS settings) to 0.98 and 0.99 in the NR-based approach for MCS equal to 7 and 14, respectively.

For the sake of completeness, Fig. 1(c) also reports the metric in the ideal case of no interference due to IBE (curves labeled as w/o IBE). Interestingly, in most cases the PRR for the NR scheme is higher than the one measured in the legacy case without IBE. Such a trend has to be ascribed to the fact that as an additional beneficial side effect, reducing the TTI and letting a single CAM be transmitted per TTI allows a better CAM reception. Indeed, in the legacy case, when multiple CAMs are accommodated in the same 1ms-long TTI, due to the usage of half-duplex transceivers, a VUE cannot receive CAMs while transmitting. The improvement is larger for $T_{\text{TTI}}=0.25$ ms, since up to 3 CAMs per TTI can be lost in the legacy case due to such limitation. As the transmitter-receiver distance increases, the larger noise contribution due to the usage of larger SCS makes the improvement weaker for the NR scheme compared to the legacy scheme without IBE (see the curves corresponding to MCS 7, above 140 m). Indeed, successful reception (i.e., SINR larger than the minimum threshold) for decreased received power is more hardly achieved.

The better performance of the NR-based scheme compared to the legacy one translates also in lower UD values, as shown in Fig. 2(c).

V. Conclusion

This paper evaluated the performance of the sensing-based SPS scheme in C-V2X Mode 4 augmented with the NR flexible numerology. Interestingly, achieved simulation results show that a larger spacing between subcarriers and a shorter
TTI duration allow to significantly increase the PRR (and, consequently, reduce the UD). The main reason for this improvement has been shown to be the IBE reduction allowed by the translation of orthogonality in the frequency domain to orthogonality in the time domain. This effect is more relevant than the increased noise due to the larger SCS. As a further advantage, the impact of half-duplex limitations is also reduced. The value of the conducted study is further legitimated by the fact that the scalable SCS setting can be beneficially exploited under high-mobility settings, hence motivating to investigate more deeply joint effects at PHY and MAC layers.

REFERENCES


