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# On Wireless Blind Spots in the C-V2X Sidelink

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***Abstract*—The Third Generation Partnership Project (3GPP) has issued specifications for the autonomous assignment of radio resources by vehicles on the sidelink of the cellular-vehicle-to-everything (C-V2X) technology. It is based on a sensing mechanism for resource selection and a semi-persistent scheduling for resource reservation to periodic safety messages. Imperfect sensing due to hidden terminals and to half-duplex on board transceivers may result in the selection of interfered resources for successive message transmissions. As a consequence of the lost packets, involved vehicles may become blind to the presence of other vehicles in their vicinity even for many seconds, with threats to the road safety. In this paper, we define these events as *wireless blind spot*s (WBSs) and characterize their probability to occur. We propose an enhancement to the autonomous mode in order to reduce the WBS duration and demonstrate the benefits of the proposal against the legacy mode, both analytically in a simplified scenario and through simulations in a highway environment.**

***Index Terms*—Cellular-vehicle-to-everything, 5G, New Radio, sidelink, autonomous mode, mode 4, mode 2a**

## I. INTRODUCTION

The growing interest in connected and autonomous vehicles and the relevant expectation of huge market growth has led the Third Generation Partnership Project (3GPP) to specify, starting from long term evolution (LTE) Rel. 14, some amendments to support the cellular-vehicle-to-everything (C-V2X) technology [1]. Emphasis is given to the short-range direct communications among vehicles on the *sidelink* radio interface for the exchange of periodic status update messages, hereafter called *beacons*[1]. They are sent with a periodicity (denoted as beacon period, $T_{\mathrm{B}}$) between 1 s and 100 ms, or even lower, to inform the neighbours about the vehicle's type, location, direction, speed, intended manoeuvres, etc.

The selection of sidelink resources for beacon transmissions can be made *autonomously* by a vehicle, whether it is inside or outside the coverage of a base station, following an algorithm based on channel sensing and semi-persistent scheduling (SPS). Each vehicle monitors the channel for a given time interval, identifies those resources that are the least interfered, and selects randomly among them the one for its beacon transmission. Once a resource is chosen, the same allocation can be kept with a given probability for successive transmissions.

Some factors can determine a "wrong" resource selection in the autonomous mode, i.e., the choice of a resource that is also selected by an undetected vehicle. First, sensing can be imperfect due to hidden vehicles. Second, half-duplex devices cannot sense while transmitting, so they cannot detect other vehicles occupying their own resource or an adjacent (in the frequency domain) resource. Third, the selection after sensing is made randomly on a restricted pool of least interfered resources, so more vehicles could select the same resource for their beacon transmissions.

Any incorrect resource choice that is kept for successive transmissions may cause bursts of losses lasting several seconds, thus generating a threat to road safety. Indeed, if several consecutive beacons are lost from a generic vehicle, this means that its real position and movements are no longer known for some time. This could be especially detrimental, for example when the "invisible" vehicle performs an overtaking manoeuvre, with a lane change which cannot be tracked by its neighbors.

These issues motivate the contributions of our study:

- We characterize analytically the probability that what we call here *wireless blind spot*s (WBSs) occur, i.e., that successive packets are lost for a given time interval duration, due to wrong sidelink resource selection in the autonomous mode.
- We propose an extension to the legacy autonomous mode in order to limit the maximum duration of any wrong resource allocation to controllable values.
- We demonstrate the relevance of the risk of WBSs and the effectiveness of the proposal in limiting them through simulations in a highway scenario under realistic settings.

The remainder of this paper is organized as follows. Section II provides an overview of the C-V2X autonomous mode technology. The proposal is discussed in Section III, where an analytical model is derived and also validated. Extensive simulation results are reported in Section IV before concluding in Section V.

## II. C-V2X AUTONOMOUS MODE: AN OVERVIEW

The C-V2X autonomous mode has been specified as Mode 4 in Release 14/15 to support basic V2X safety services [2].

Although the 5G new radio (NR) standardization is ongoing to support advanced applications in future Release 16, the new autonomous mode, named Mode 2(a), is expected to be based on the same sensing with SPS procedure of Mode 4 [2].

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[1] Beacons are referred to as cooperative awareness messages (CAMs) by the European Telecommunications Standards Institute (ETSI) and as basic safety messages (BSMs) by the Society of Automotive Engineers (SAE).

The single carrier frequency division multiple access (SC-FDMA) on the sidelink uses a resource granularity given by the subchannel in the frequency domain and the transmission time interval (TTI) in the time domain. One subchannel includes a given number of resource blocks (RBs), set by the operator, each formed by 12 orthogonal frequency division multiplexing (OFDM) subcarriers, spaced of an amount that depends on the numerology. A TTI includes 14 OFDM symbols, whose duration also depends on the numerology.

A sidelink control information (SCI), associated to each beacon message, is sent during the same TTI and carries information about the currently occupied resource and the reserved ones for successive beacon transmissions. A vehicular device continuously estimates whether a resource has been (will be) used, based on: 1) the decoded SCIs; and 2) a comparison of the measured reference signal received power (RSRP) with a given threshold. Based on the information collected in a *sensing window* that lasts 1 second before the beacon generation, the pool of the 20% least interfered resources is identified. One of these resources is selected randomly by the vehicle. The same allocation is then periodically granted to successive beacons for a number of $T_{\mathrm{B}}$ periods, which is set to a random value between a minimum $n_{\min}$ and a maximum $n_{\max}$ that depend on the beacon frequency. Once the corresponding time has elapsed, here called *time before evaluation* (TBE), a test is performed on the resource allocation: with probability $p_{\mathrm{k}}$, referred to as *keep probability*, the same allocation is maintained and a new random number of $T_{\mathrm{B}}$ periods is selected: with probability $1-p_{\mathrm{k}}$, the resource allocation is instead modified. Thus, the duration over which the node maintains the same allocation, here called *time before change* (TBC), corresponds to a number of TBE intervals that is unbounded if $p_{\mathrm{k}} > 0$. This process is repeated over time, but it does not prevent two or more vehicles to select the same resource after sensing, causing reciprocal interference with possible consecutive (i.e., persistent) collisions. In addition, today devices are half duplex and cannot hear each other any time they use resources in the same TTI. Undetected collisions, due to half-duplex limitations or hidden terminals, make vehicles *blind* to the presence of other vehicles from which they miss periodic beacons, until the next change of resource is triggered.

Studies in the literature showed that the value of $p_{\mathrm{k}}$ (set by the operator between 0 and 0.8) strongly affects the trade-off between reliability and up-to-dateness of beacons [3]–[5]. If $p_{\mathrm{k}}$ is close to zero, the resources are more frequently changed and the reliability of the sensing procedure is reduced, increasing the probability of a wrong estimation of the resource occupancy status and dramatically decreasing the packet reception ratio (PRR). If $p_{\mathrm{k}}$ is close to 0.8, the sensing is more reliable, which normally allows the highest PRR [4], [5], but any incorrect resource choice may last longer and cause bursts of losses (i.e., long duration of WBS events) that reduce the up-to-dateness of received beacons. In short, wrong resource selections are more likely to occur but have shorter duration when $p_{\mathrm{k}}$ is low (which results in low PRR and low WBS occurrences), whereas they are less likely but have longer duration, and hence more harmful effects due to persistent collisions, when $p_{\mathrm{k}}$ is high (which results in high PRR and high WBS occurrences).

In this work, we intend to achieve a trade-off between these two behaviours of the legacy protocol and to find a way to reduce the duration of WBS events while keeping the PRR at high values.

## III. ENHANCED C-V2X AUTONOMOUS MODE: PROTOCOL DESCRIPTION, MODELING AND ANALYSIS

### A. *Position of the problem and proposed protocol*

As explained, in the autonomous mode the same resource can be kept for a duration which is theoretically not limited for any value of $p_{\mathrm{k}} > 0$. At the same time, as also shown for example in [3]–[5], a low value of $p_{\mathrm{k}}$ causes a degradation of the PRR performance. The aim of our work is to enhance the SPS procedure by reducing the duration of a potentially wrong selection of resources, without the need to use a smaller $p_{\mathrm{k}}$.

This objective is achieved by setting a limit to the number of consecutive TBE intervals the resource can be kept. Such limit is a parametric value called *maximum keep times* and denoted as $\hat{m}_{\mathrm{k}}$. The flow chart of the proposal is shown in Fig. 1, where the white blocks represent the legacy procedures and the red blocks refer to the proposed modifications. Specifically, as in the legacy protocol, a selected resource is initially used for a number of $T_{\mathrm{B}}$ periods ($n$ in Fig. 1) randomly chosen between $n_{\min}$ and $n_{\max}$. When such time passes (i.e., the resource reselection counter expires), the same resource can be further kept for another TBE with probability $p_{\mathrm{k}}$ (as in the legacy protocol), but only if it has been kept for a number of TBE intervals lower than $\hat{m}_{\mathrm{k}}$. At the reselection counter expiration, the resource is changed with probability $1-p_{\mathrm{k}}$ (legacy) or if $\hat{m}_{\mathrm{k}}$ is reached, regardless the value of $p_k$ (proposal).

In the rest of this section, we develop a probabilistic modeling of the proposed protocol in the simplified scenario where two vehicles cannot sense each other's reservation (e.g., because they are just entering the reciprocal range). Our aim is to find an analytical closed-form expression for the *wireless blind spot probability* (WBSP) in order to assess the impact of $\hat{m}_{\mathrm{k}}$ on the beacon performance and the duration of wireless blind spots. Results in scenarios with hundreds of nodes, assuming accurate C-V2X PHY and MAC modeling, are then obtained via simulation in Section IV.

### B. *Probabilistic modeling*

Let $D_m$ be a random variable (rv) modeling the decision to maintain the resource after the $m$-th TBE. We assume that the successive decision steps $D_1, D_2, \ldots$ are independent identically distributed (i.i.d.) rvs, and, $\forall m$, $D_m$ has a Bernoulli discrete distribution of parameter $p_{\mathrm{k}}$. Let $N_{\mathrm{BE}m}$ a non-negative integer-value rv modeling the number of beacon periods of the $m$-th TBE. The rvs $N_{\mathrm{BE}1}, N_{\mathrm{BE}2}, \ldots$ are i.i.d. and have a uniform discrete distribution

$$P_{N_{\mathrm{BE}m}}(l) = \begin{cases} \frac{1}{n_{\max}-n_{\min}+1} & \text{for } l \in [n_{\min}, n_{\max}] \\ 0 & \text{otherwise} \end{cases} \qquad (1)$$

which represents the probability that the $m$-th TBE lasts for $l$ beacon periods. Let $M$ be a non-negative integer-value rv

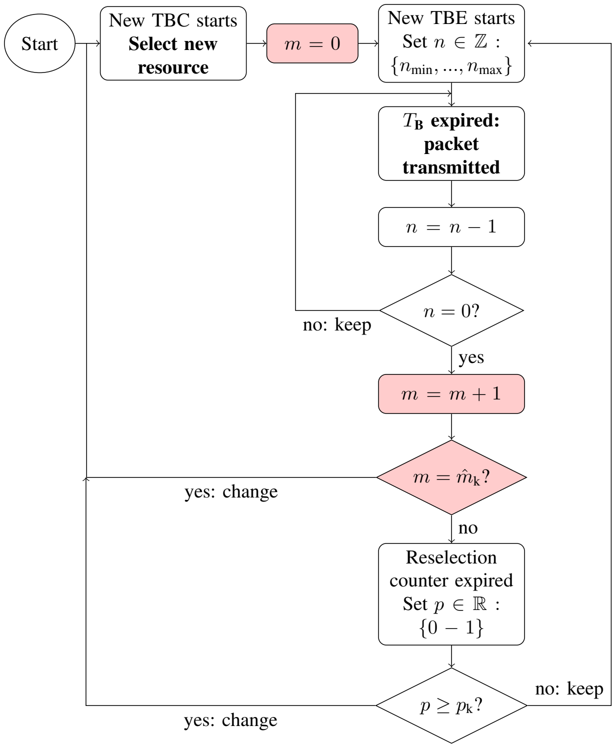


Fig. 1. Flow chart of resource allocation. White boxes represent the legacy 3GPP specifications. Red boxes are the proposed additions.

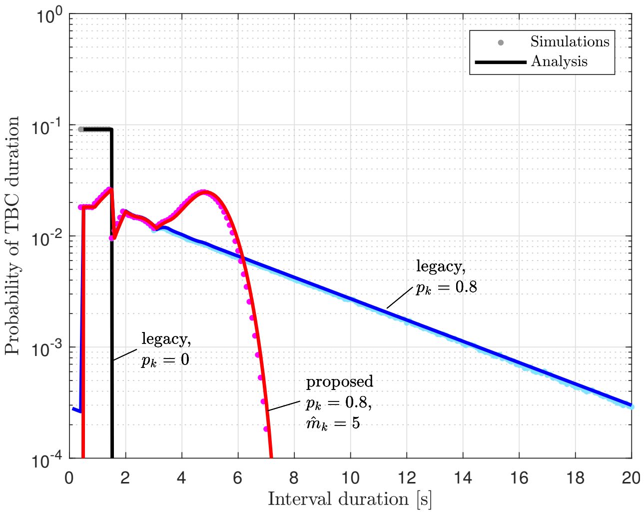
modeling the number of decision steps between two distinct resource allocations. Since the decision steps are independent, $M$ has a First Success discrete distribution of parameter $1-p_\mathrm{k}$ (the "success" here being the change of resource allocation after a certain number of decision steps), that is

$$P_M(m) = \begin{cases} (1-p_\mathrm{k})p_\mathrm{k}^{m-1} & \text{if } 1 \leq m < \hat{m}_\mathrm{k} \\ p_\mathrm{k}^{\hat{m}_\mathrm{k}-1} & \text{if } m = \hat{m}_\mathrm{k} \end{cases} \tag{2}$$

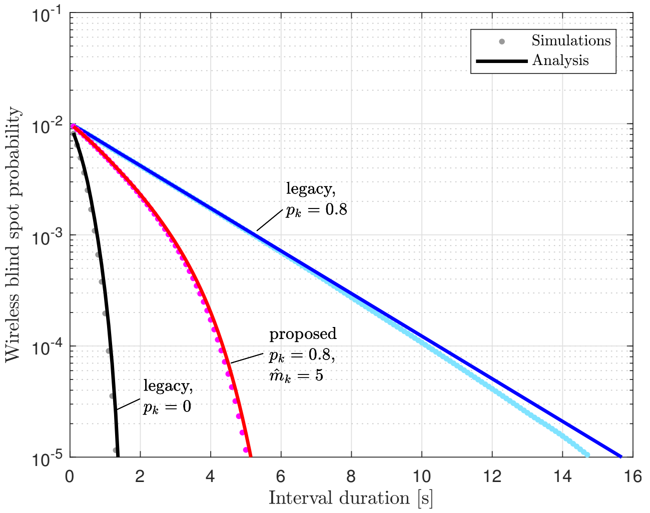
which represents the probability that the TBC includes $m$ TBEs. Finally, let $N_\mathrm{BC}$ be the rv modeling the number of beacon periods before a change of resource allocation. We can write:

$$N_\mathrm{BC} = \sum_{m=1}^{M} N_{\mathrm{BE}m} \tag{3}$$

where $M$ is independent of the sequence $\{N_{\mathrm{BE}m}\}_m$. We note that Eq. (3) is the source of a simple random walk model.



(a) Probability of time before change duration.



(b) Wireless blind spot probability.

Fig. 2. Simplified two-vehicles scenario. Analytical results Vs. simulations (beacon frequency 10 Hz; $n_\mathrm{min}$=5, $n_\mathrm{max}$=15). Proposed solution with $p_\mathrm{k} = 0.8$ and $\hat{m}_\mathrm{k} = 5$ compared to the legacy algorithm with $p_\mathrm{k} = 0$ and $p_\mathrm{k} = 0.8$.

### *C. Probabilistic analysis*

The first moment of $N_\mathrm{BC}$ is given by

$$\mathbb{E}[N_\mathrm{BC}] = \left[\frac{n_\mathrm{min} + n_\mathrm{max}}{2}\right]\left[\frac{1 - p_\mathrm{k}^{\hat{m}_\mathrm{k}}}{1 - p_\mathrm{k}}\right] \tag{4}$$

by direct application of Wald's lemma. The maximum number of beacon periods between two distinct resource allocations is $n_\mathrm{max}\ \hat{m}_\mathrm{k}$. Thus, while $p_\mathrm{k}$ still allows to control the probability of maintaining the same resources statistically for more or less time, the parameter $\hat{m}_\mathrm{k}$ can be used to set a desired maximum duration. The discrete distribution of $N_\mathrm{BC}$, conditional on a given number $m$ of decision steps, is the convolution of $m$ distributions

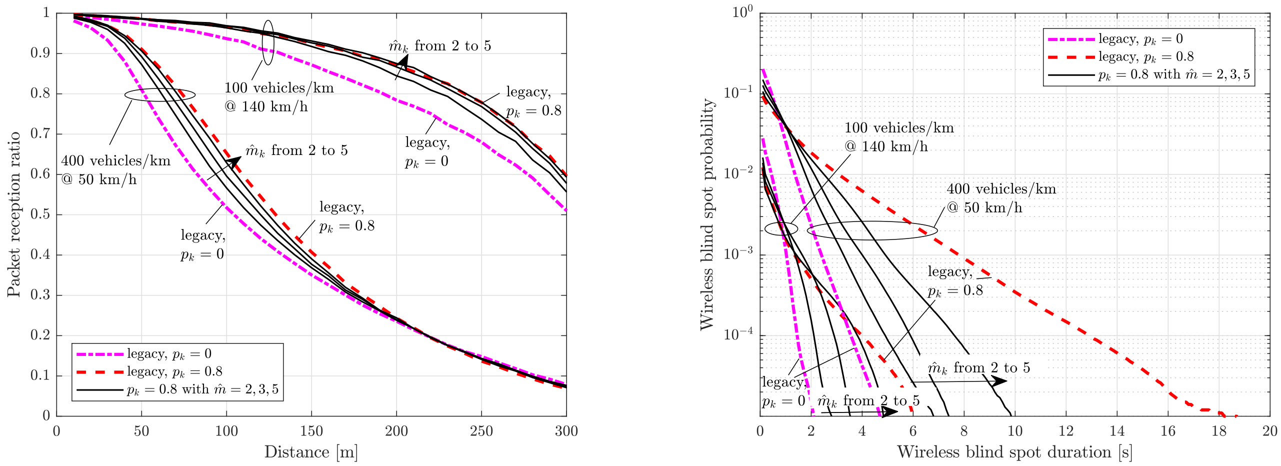
$$P_{N_\mathrm{BC}|m}(l) = \sum_{\substack{l_1, l_2, \ldots, l_m \\ l_1 + l_2 + \ldots + l_m = l}} \prod_{j=1}^{m} P_{N_{\mathrm{BE}_j}}(l_j) \tag{5}$$

whose evaluation is more easily done in the Fourier domain. Let $\mathbf{P}_X$ denote the discrete distribution of a non-negative integer-value rv $X$ written as a vector, i.e., $\mathbf{P}_X \triangleq [P_X(1), P_X(2), \ldots]$. Let $\mathcal{F}_d$ (resp. $\mathcal{F}_d^{-1}$) denote the discrete Fourier transform (resp. inverse discrete Fourier transform) of a vector. We can express $\mathbf{P}_{N_\mathrm{BC}|m}$ as

$$\mathbf{P}_{N_\mathrm{BC}|m} = \mathcal{F}_d^{-1}[(\mathcal{F}_d[\mathbf{P}_{N_\mathrm{BE}}])^m] \tag{6}$$

where elevation to power $m$ is done element-wisely. Then, by the law of total probability,

$$P_{N_\mathrm{BC}}^{(\hat{m}_\mathrm{k})}(l) = \sum_{m=1}^{\hat{m}_\mathrm{k}} P_{N_\mathrm{BC}|m}(l) P_M(m) \tag{7}$$



(a) PRR vs. distance.

(b) WBSP vs wireless blind spot duration.

Fig. 3. Comparing the proposed solution, with $p_\mathrm{k} = 0.8$ and $\hat{m}_\mathrm{k} = 2, 3, 5$, to the legacy algorithm with either $p_\mathrm{k} = 0$ or $p_\mathrm{k} = 0.8$. Highway scenario, with 100 vehicles/km at 140 km/h and 400 vehicles/km at 50 km/h.

which corresponds to the probability that the generic TBC lasts for $l$ beacon periods, given the adopted $\hat{m}_\mathrm{k}$. Obviously, $P^{(1)}_{N_\mathrm{BC}}(l) = P_{N_\mathrm{BC}}(l)|_{p_\mathrm{k}=0}$ (i.e., the proposal with $\hat{m}_\mathrm{k} = 1$ is equivalent to the legacy algorithm with $p_\mathrm{k} = 0$) and, in the limit $\hat{m}_\mathrm{k} \to \infty$, we obtain the $N_\mathrm{BC}$ distribution of the legacy algorithm. Eq. (7) is validated with simulations in Fig. 2(a), showing a perfect matching with the analysis.

### *D. Derivation of the WBSP in the two-vehicle scenario*

Let $E_n$ be the event: at least one change of resource occurs in an observation window of $n$ beacon periods and $\bar{E}_n$ the complementary event. $E_1$ is the event: the change of resource occurs in a given beacon period. Let $H_i$ be the event: a change of resource occurred $i$ beacon periods before the beginning of an observation window of $n$ beacon periods. A property of the proposed protocol is that

$$P(H_i) = P(E_1), \forall i \geq 0 \tag{8}$$

i.e., the probability to have a change of resource in a given beacon period does not depend on the beacon period index. Next, from the previous definitions of events, we get

$$P(\bar{E}_n|H_i) \simeq P(N_\mathrm{BC} \geq i+n) = \sum_{l=i+n}^{\infty} P^{(\hat{m}_\mathrm{k})}_{N_\mathrm{BC}}(l) \tag{9}$$

where we neglect the event that another change occurs between $i$ beacon periods before the observation window and its beginning. By the law of total probability

$$P(\bar{E}_n) = \sum_{i=0}^{\infty} P(\bar{E}_n|H_i)P(H_i) = P(E_1) \sum_{i=0}^{\infty} \sum_{l=i+n}^{\infty} P^{(\hat{m}_\mathrm{k})}_{N_\mathrm{BC}}(l)\,. \tag{10}$$

Eq. (10) is valid $\forall n \geq 1$, and thus in particular for $n = 1$, which allows to find out $P(E_1)$. Finally

$$P(\bar{E}_n) = \frac{\sum_{i=0}^{\infty} \sum_{l=i+n}^{\infty} P^{(\hat{m}_\mathrm{k})}_{N_\mathrm{BC}}(l)}{1 + \sum_{i=0}^{\infty} \sum_{l=i+n}^{\infty} P^{(\hat{m}_\mathrm{k})}_{N_\mathrm{BC}}(l)} \triangleq p_\mathrm{unchanged}(n) \tag{11}$$

which is the probability that in a generic time window covering $n$ beacon periods, the resource is not changed. Given a certain number $r$ of TTIs per beacon period, the probability that two nodes use the same TTI in a beacon period is $1/r$, under the simplifying assumption that they choose the resource randomly. Thus, the probability, referred to as WBSP and denoted $p_\mathrm{wbs}(n)$, that, in an observation window of $n$ beacon periods, the two nodes cannot see each other and collide repeatedly, is equal to the probability that they are using the same TTI and none of them change its resource allocation, i.e.,

$$p_\mathrm{wbs}(n) = \frac{[p_\mathrm{unchanged}(n)]^2}{r}\,. \tag{12}$$

Eq. (12) is validated with simulations in Fig. 2(b), showing perfect matching with the analysis. In the same Figure, the proposal has a dramatic impact on the duration of the blind spot periods. In particular, for $p_\mathrm{k} = 0.8$ with the legacy algorithm a wireless blind spot lasting 10 s ($n$=100) occurs with probability $10^{-4}$. At a speed of 100 km/h, this means loosing updates from neighbouring vehicles when traveling for more than 250 m. With the proposed solution and assuming $\hat{m}_\mathrm{k} = 5$, instead, any wireless blind spot lasting more than approximately 5 s occurs with a probability which is more than one magnitude lower than $10^{-4}$.

## IV. LARGE-SCALE SIMULATIONS

Results from large-scale simulations using the open-source LTEV2Vsim simulator [6],[2] well calibrated over C-V2X Mode 4, are provided in Figs. 3 and 4. A highway scenario is simulated under three vehicle density conditions: 100 vehicles/km at 140 km/h (light traffic), 200 vehicles/km at 100 km/h (medium traffic), or 400 vehicles at 50 km/h (congested traffic). Vehicles are positioned following a 1-D Poisson distribution as for example in [7], [8]. The WINNER+ Model B path loss model with correlated shadowing is assumed, as suggested

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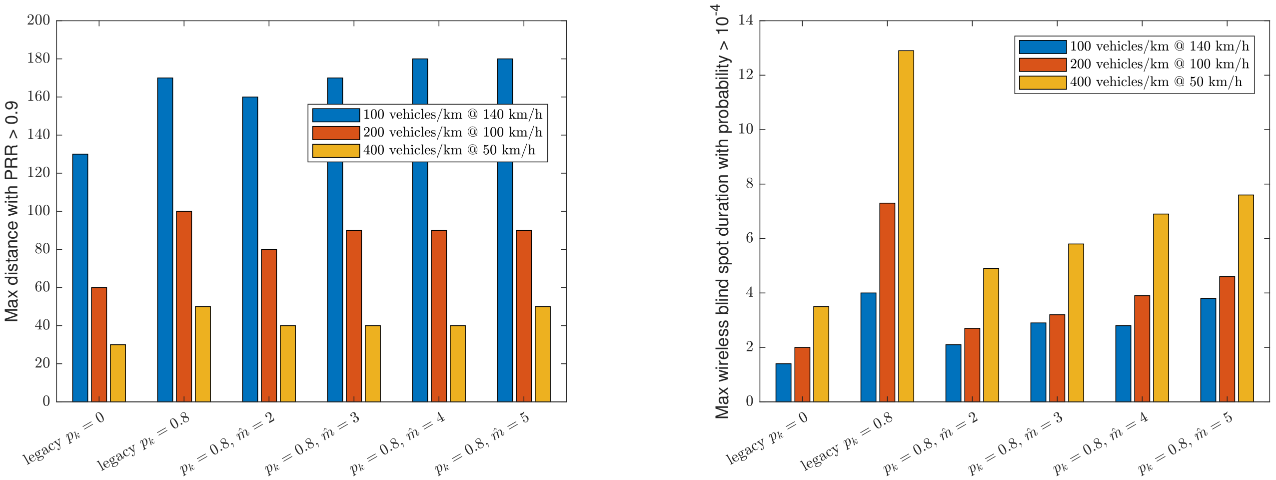
[2] Available at https://github.com/alessandrobazzi/LTEV2Vsim



(a) Maximum distance with PRR higher than 0.9.

(b) Maximum WBS duration with probability higher than $10^{-4}$.

Fig. 4. Comparing the proposed solution, with $p_\mathrm{k} = 0.8$ and $\hat{m}_\mathrm{k} = 2, 3, 4, 5$, to the legacy algorithm with either $p_\mathrm{k} = 0$ or $p_\mathrm{k} = 0.8$. Highway scenario, with 100 vehicles/km at 140 km/h, 200 vehicles/km at 100 km/h, and 400 vehicles/km at 50 km/h.

by 3GPP. Beacons of 300 bytes are transmitted at 10 Hz. The transmission power is set to 23 dBm plus antenna gains of 3 dB, with a noise figure of 9 dB. The modulation and coding scheme (MCS) index 6 is adopted with a minimum received signal to noise and interference ratio (SINR) of 5.79 dB, as detailed in [9].

In Fig. 3, the proposed solution with $p_\mathrm{k} = 0.8$ and $\hat{m}_\mathrm{k} = 2$, 3, or 5 is compared to the legacy algorithm with $p_\mathrm{k} = 0$ or $p_\mathrm{k} = 0.8$, both in terms of PRR over distance and WBSP. Two scenarios with light and congested traffic conditions are considered. The proposal guarantees a PRR almost as high as with the legacy algorithm with $p_\mathrm{k} = 0.8$. At the same time, the WBSP is significantly reduced. This is especially visible for the case with 400 vehicles/km, when the legacy protocol with $p_\mathrm{k} = 0.8$ is characterized by WBSs of duration higher than 10 s occurring with probability higher than $10^{-4}$.

The impact of $\hat{m}_\mathrm{k}$ is further investigated in Fig. 4 that shows the maximum distance to have a value of PRR higher than 0.9 [10] and the maximum WBS duration to have a probability higher than $10^{-4}$, assuming the legacy protocol with $p_\mathrm{k} = 0$ or $p_\mathrm{k} = 0.8$ or the proposed solution with $p_\mathrm{k} = 0.8$ and $\hat{m}_\mathrm{k}$ between 2 and 5. Also in these two figures we can appreciate the trade-off between PRR and WBSP and the effectiveness of the proposed solution to provide a high value of PRR without causing a high probability of long WBSs. The results related to the PRR show us that a small value of the parameter $\hat{m}_\mathrm{k}$ is sufficient to approach the PRR of the legacy protocol with $p_\mathrm{k} = 0.8$.

## V. CONCLUSION

In this paper, we have described and analyzed the risks in sidelink C-V2X autonomous mode due to the probability that a vehicle loses several consecutive status messages from one of its neighbors, which we call WBS.

We have then proposed and evaluated an extension to the legacy algorithm that can significantly alleviate this risk, without impacting on transmission reliability. The proposal has the virtue of simplicity: a vehicle just needs to keep an additional parameter ($\hat{m}$) that is used to set a limit to the maximum duration a resource can be kept.

Analytical results, validated by simulations in a simple scenario, and results of a large-scale simulation campaign under realistic settings confirm the supremacy of the proposal against the legacy protocol. It limits the WBSP to controllable values, without any negative impact on the PRR. This trade-off is crucial in many basic and advanced V2X applications.

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