Adaptive Repetition Strategies in IEEE 802.11bd V2X Networks

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***Abstract*—Vehicle-to-everything (V2X) communications have very strict throughput and latency requirements, even in scenarios with high mobility. IEEE 802.11bd is being developed as a WiFi amendment to improve V2X performance, allowing up to three repetitions per packet, along with other features. Message repetitions increase time diversity and enable maximum ratio combining at the receiver, thus improving the probability of correct decoding. This paper investigates the IEEE 802.11bd packet repetition feature. First, we analyze how the increased channel load due to repetitions may in some cases result in a higher collision rate leading to lower network performance. Then, we propose two strategies for exploiting the IEEE 802.11bd repetition feature. The proposed strategies use the channel busy ratio to adapt the number of transmissions to the channel load and are validated through network-level simulations, which account for both the acquisition and decoding processes. Results show that the proposed strategies improve network performance under variable traffic conditions and enable fair access to the channel.**

***Index Terms*—V2X, IEEE 802.11bd, connected vehicles, repetitions.**

I. INTRODUCTION

V2X communications represent a key technology for traffic safety as they can be used by vehicles to inform neighbors about their own status; in future implementations, they will also include information about the sensed environment and coordinated maneuvers. After decades of research and experiments [1], [2], [3], [4], [5], V2X based on the IEEE 802.11p standard is reaching the mass market in Europe.

Given the increased interest in V2X and the necessity to improve its efficiency and reliability, a new IEEE WiFi Task Group was established targeting the new amendment IEEE 802.11bd, with the following objectives: i) improve V2X performance, with higher spectral efficiency, increased reliability, and extended range; and ii) smooth the transition between IEEE 802.11p and the IEEE 802.11bd, with attention to coexistence, backward compatibility, interoperability, and fairness.[1]

Many new features will be introduced by the IEEE 802.11bd [6], [7]: new modulation and coding schemes (MCSs) based on low-density parity-check (LDPC) or dual carrier modulation (DCM); a known pilot sequence, namely midamble, to improve channel estimation; the possibility to use channel bonding and mmWave bands; and, finally, the possibility to retransmit the same packet up to four times (i.e., with three repetitions after the first transmission) as a burst.

Retransmissions are in general a commonly used method to increase the packet reception ratio (PRR). In the case of unicast communications, after each transmission, acknowledgment messages can be sent back from the receiver [4]. Differently, such acknowledgment mechanism is not feasible in the broadcast case. Blind retransmissions, i.e. retransmission mechanisms that do not rely on any feedback from the receiver, have been already adopted by long term evolution (LTE)-V2X and 5G new radio (NR)-V2X sidelink [8], [9].

In the upcoming IEEE 802.11bd, up to three repetitions can be set to follow the first transmission of the packet, which all carry exactly the same data. The probability of correct packet decoding is inherently improved by the increased time diversity and, additionally, receivers can apply maximum ratio combining (MRC) on the received signals to further increase the reliability of the communication. Nevertheless, repetitions also increase channel load, which may imply a higher collision probability. Consequently, an accurate performance evaluation at the network level is crucial to understand the effects of retransmissions and in particular the trade-off between reliability and channel load. Existing studies on packet repetitions primarily examine physical layer aspects, e.g., focusing on the probability of correct reception on a generic link without interference, as in [7] and related works, whereas only [10] provides early results on the impact of packet repetitions on network performance.

The definition of repetition strategies, i.e. determining how many repetitions to transmit, is particularly important and challenging as it guides the trade-off between reliability and channel load. The decision needs in fact to be performed locally depending on the channel congestion, which can itself be affected by the decisions made by the nodes.

The scope of this paper is twofold: i) we analyse the impact of the repetitions on the performance from a network point of view, considering different channel models, varying the vehicles' densities, and including the effects of preamble detection (i.e., considering that the received signals can only be combined when their preambles are detected); ii) we propose two adaptive strategies, called *deterministic* and *probabilistic*, to opportunistically set the number of repetitions in order to maximise the network performance. The proposed approach is distributed, as it leverages on an adapted version of the channel busy ratio (CBR), which is a metric already measured at each single node. Results, obtained by the use of an open-source simulator, show that the proposed approach is effective and enables fair access to the channel.

The rest of this paper is organized as follows. Section II presents the repetition mechanism for IEEE 802.11bd. Section III introduces the proposed adaptive repetition strategies. Section IV presents the simulation results. Finally, Section V provides our conclusion.

II. REPETITIONS IN IEEE 802.11BD

In this section, we first briefly introduce the retransmission mechanism of IEEE 802.11bd; then, we consider the impact of repetitions on two metrics: the signal-to-interference-plus-noise ratio (SINR), which is related to the communication reliability and is used for performance evaluation, and the CBR, which describes the channel load and is exploited by the designed repetition strategies.

As a feature of IEEE 802.11bd, up to three repetitions can be optionally performed after the first transmission of the packet. More specifically, as exemplified in Fig. 1, a station accesses the channel

Manuscript received 28 June 2022; revised 19 December 2022; accepted 24 January 2023. Date of publication 2 February 2023; date of current version 20 June 2023. This work was supported by European Union through Italian National Recovery and Resilience Plan (NRRP) of NextGenerationEU and in part by the Partnership on "Telecommunications of the Future" through Program "RESTART" under Grant PE00000001, and by the China Scholarship Council that is supporting Wu Zhuofei during his visiting scholarship at the University of Bologna. The review of this article was coordinated by Prof. Jun Zheng. *(Corresponding author: Alessandro Bazzi.)*

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Digital Object Identifier 10.1109/TVT.2023.3241865

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[1] The new amendment is expected to be published by the beginning of 2023.

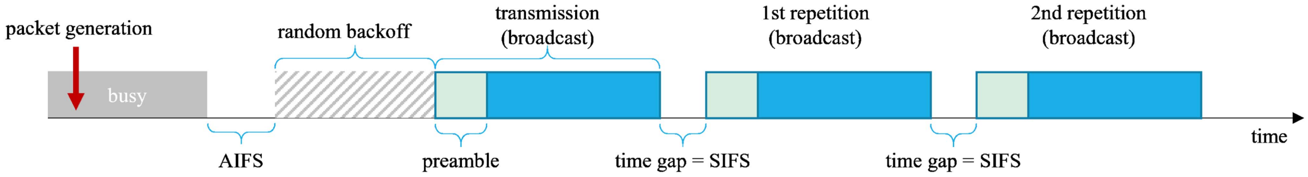

Fig. 1. An example of broadcast transmission with two repetitions. At the packet generation, the channel is sensed as busy. Once the busy condition ends, the transmission starts after sensing the medium idle for a time interval (AIFS) followed by the random backoff. Two repetitions follow the first transmission, separated by a time gap (SIFS, which is shorter than the AIFS). Each transmission starts with a preamble indicating the presence of the packet. Given that the transmissions are in broadcast, no acknowledgment is returned.

through the carrier sense multiple access with collision avoidance (CSMA/CA) mechanism which requires that the medium is idle for at least an arbitration inter-frame space (AIFS); the repetitions that may follow the first transmission are then separated by a time gap lasting a short inter-frame space (SIFS), which is shorter than the AIFS, thus ensuring that the use of the channel is not released.

In 802.11bd, each packet consists of preamble and data field. The receiver can decode the data field only if it firstly detects the preamble. At the receiver side, once the packet is correctly decoded, the subsequent repetitions are ignored. Otherwise, the receiver can store the signals of the undecoded packets for which the preambles are detected. Such stored signals can be combined through MRC to improve the probability of correct reception of the packet. Note that if the preamble is not detected, the receiver is not aware of the presence of the signal and cannot perform the storage and MRC.

SINR with repetitions: The SINR corresponding to the jth transmission can be modeled as

$$\rho_j = \frac{P_{\mathrm{r}j}}{P_{\mathrm{n}} + \sum_{i \in \mathcal{I}_j} P_{\mathrm{I}ji}} \tag{1}$$

where $P_{\mathrm{r}j}$ is the received power; P_{n} is the average noise power; $\mathcal{I}_j$ is the set of nodes that are interfering with the reception under examination; and $P_{\mathrm{I}ji}$ is the average power from the ith interferer. Then, the average SINR of the signals combined by the MRC receiver can be modeled as

$$\rho = \sum_{j=1}^{M} \alpha_j \cdot \rho_j \tag{2}$$

where M is the total number of transmissions, including the first transmission and the repetitions; $\alpha_j = 1$ if the preamble is detected, otherwise $\alpha_j = 0$.

Net CBR: The decision on the number of repetitions N_{rep} to be transmitted needs to be made autonomously by each station, based on its knowledge about the channel load. To this aim, the station already collects the CBR [11], which is a metric used for congestion control and is defined as the average time for which the signal received from the other stations has a power above a given threshold θ_{CBR}, and it is updated every T_{CBR}. However, the CBR depends on the number of repetitions, and therefore we here define the *net CBR*, also updated every T_{CBR}, calculated as

$$\gamma = T_{\mathrm{net}} / T_{\mathrm{CBR}} \tag{3}$$

where T_{CBR} is the duration of the observation and T_{net} is the sum of the intervals during T_{CBR} where the first detected copy of a packet is received and the power of the received signal is above the threshold θ_{CBR}. The use of the net CBR in place of the total CBR is necessary to avoid a loop triggering, in which the decision on the number of repetitions relies on a metric which in turn depends on the decision itself. Note also that the identification of the first copy of a packet is easily performed by the receiving station, since the repetitions that follow are spaced by a short SIFS gap.

III. REPETITION STRATEGIES

In this Section, we first introduce a general approach for setting the number of repetitions based on the channel load and then specify two strategies (called *deterministic* and *probabilistic*) that can be distributively applied by the stations. To this scope, the number of repetitions will be derived as a function of a target network performance metric (e.g., the packet reception ratio) and the net CBR to take into account the reliability vs. channel load trade-off.

General Approach: We propose two strategies where each station autonomously sets the number of repetitions so that a target performance metric $\psi(\gamma, N_{\mathrm{rep}})$ is optimized. The target performance metric $\psi(\gamma, N_{\mathrm{rep}})$ (which can represent, e.g., the maximum distance for a given PRR) is a function of the net CBR, and also depends on the number of repetitions N_{rep}. In both the proposed strategies, the net CBR domain is divided into intervals and each interval is associated with an average number of repetitions $\overline{N}_{\mathrm{rep}}(\gamma)$. The $\overline{N}_{\mathrm{rep}}(\gamma)$ is thus a non-increasing step function of the net CBR. Then, the number of repetitions N_{rep} is determined based on $\overline{N}_{\mathrm{rep}}(\gamma)$, in a different way for the two strategies.

Net CBR intervals: For a fixed number of repetitions N_{rep}, it is expected that the performance $\psi(\gamma, N_{\mathrm{rep}})$ decreases with γ. In fact, an increase in data traffic (e.g., higher vehicle density, larger packets, more frequent packet generation), which corresponds to an increase in the net CBR γ usually degrades the communication performance. Moreover, if the channel is not congested (lower values of γ), an increase in the repetitions can benefit the performance (i.e., $\psi(\gamma, N+1) > \psi(\gamma, N)$ for lower values of γ). Differently, under a higher channel load, a further increase in repetitions can degrade the performance (i.e., $\psi(\gamma, N+1) < \psi(\gamma, N)$ for higher values of γ). The value of γ where $\psi(\gamma, N+1)$ and $\psi(\gamma, N)$ intersect thus represents a threshold below which $N+1$ repetitions are preferable to N and above which the opposite is true.

Based on such considerations, we divide the net CBR domain [0,1] into $N_{\mathrm{max}} + 1$ intervals, where N_{max} is the maximum number of repetitions. Specifically, if the CBR falls within the ith interval, the best option is to mostly use $i-1$ repetitions. The ith interval is defined as $[\gamma_i^*, \gamma_{i-1}^*)$, with the threshold γ_i^* defined as:

$$\gamma_i^* = \gamma_i^{\#} \left[\begin{smallmatrix} \gamma_{i-1}^* \\ \gamma_{i+1}^* \end{smallmatrix} \right. \tag{4}$$

where we define $x\left[{}_L^H \triangleq \max\left(L, \min\left(x, H\right)\right)\right.$ to simplify the notation, and where $\gamma_0^* \triangleq 1$, $\gamma_{N_{\mathrm{max}}}^* \triangleq 0$, and

$$\gamma_i^{\#} = \min_{\gamma} \{\psi(\gamma, i) > \psi(\gamma, i+1)\} \, . \tag{5}$$

Equation (4) guarantees that the thresholds are correctly ordered. If $\gamma_i^* = \gamma_{i-1}^*$, it simply means that transmitting $i-1$ repetitions is not convenient.

Deterministic strategy: In the *deterministic* strategy, the station transmits an average number of repetitions that is a step function of γ, i.e.

$$\overline{N}_{\mathrm{rep}}(\gamma) = i \text{ where } \gamma_{i+1}^* \leq \gamma < \gamma_i^*, \tag{6}$$

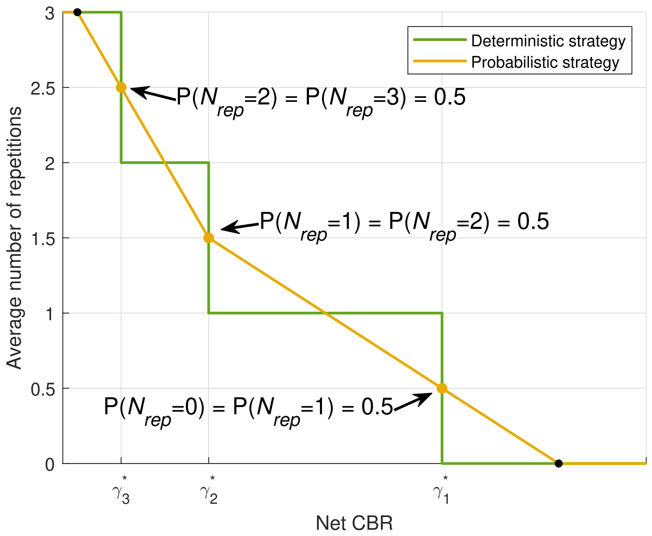

Fig. 2. Example of the average number of repetitions varying the net CBR with the two proposed strategies.

and $i = 0, 1, \ldots, N_{\max}$. The average number of repetitions for the deterministic strategy is exemplified in Fig. 2.

The number of repetitions N_{rep} is then deterministic and equal to $\overline{N}_{\text{rep}}(\gamma)$.

Probabilistic strategy: In the *probabilistic* strategy, the average number of repetitions $\overline{N}_{\text{rep}}(\gamma)$ follows a piece-wise linear function. Specifically, the station transmits an average number of repetitions equal to

$$\overline{N}_{\text{rep}}(\gamma) = n^{\#}(\gamma) \Big[_{N_{\min}}^{N_{\max}} \tag{7}$$

where $N_{\min} = 0$ and

$$n^{\#}(\gamma) = k - 0.5 + \frac{\gamma_k^* - \gamma}{\gamma_k^* - \gamma_{k+1}^*} \text{ when } \gamma_{i+1}^* \leq \gamma < \gamma_i^*, \quad i = 0, 1, \ldots, N_{\max} \tag{8}$$

where $k = i\big[_{N_{\min}+1}^{N_{\max}-1}$. The average number of repetitions for the probabilistic strategy is exemplified in Fig. 2.

The vehicle then determines N_{rep} as a random variable equal to

$$N_{\text{rep}} = \lfloor \overline{N}_{\text{rep}}(\gamma) \rfloor + \delta(\gamma) \tag{9}$$

where $\delta(\gamma)$ is a Bernoulli random variable equal to 1 with probability $p(\gamma) = \overline{N}_{\text{rep}}(\gamma) - \lfloor \overline{N}_{\text{rep}}(\gamma) \rfloor$.

This definition implies that $\delta(\gamma) = 1$ with probability $p(\gamma) = 0.5$ when the CBR value γ equals any of the thresholds γ_i^* (the orange points in Fig. 2). When the CBR is between two thresholds, such probability varies linearly with γ. The piece-wise function for γ below $\gamma_{N_{\max}}^*$ and above $\gamma_{N_{\min}+1}^*$ maintains the slope of the adjacent intervals until reaching the maximum ($N_{\max}$) and minimum ($N_{\min}$) values, respectively. As an example, when $\gamma = \gamma_2^*$, the average number of repetitions is 1.5, i.e. the station sets 1 repetition with probability 0.5 and 2 repetitions otherwise.

IV. RESULTS

In this section, we first assess the impact of repetitions assuming that all nodes adopt the same number of repetitions, and considering different modelling of the preamble detection and propagation models. Then, we show the effect of both the proposed strategies assuming a fully distributed decision. A modified version of the open-source simulator WiLabV2Xsim is used [9].[2] Table I shows the main simulation settings.

A. *On the Impact of Preamble Detection*

As described in Section II, the packet consists of a preamble and a data field. The receiver tries to decode the data field only if it first detects the preamble. Otherwise, the packet is treated as noise and cannot contribute to the MRC processing.

We now investigate the importance of correctly modelling the preamble detection process. In particular, we compare the performance at the receiver when either i) a realistic modelling is assumed, where the preamble detection is successfully performed only if the received power exceeds a given threshold, or ii) an ideal modelling is assumed, where the preamble is detected even if the received power is very low.

Results are shown in Fig. 3, where we compare the ideal preamble detection[3] with the case where the power level for preamble detection is either set to −100 dBm (Fig. 3(a)) or −103 dBm (Fig. 3(b)). The value of −100 dBm corresponds to −2 dB signal to noise ratio and is in good agreement with off-the-shelf devices [13], and therefore then used in the rest of the paper. The threshold set at −103 dBm allows to study the impact of the implementation of more advanced receivers. The results remark that wrongly modelling the preamble detection phase leads to incorrect conclusions, especially if there is a small difference between the minimum power to detect the preamble and the minimum power to decode the packet.

Looking at the realistic case of non-ideal preamble detection in Fig. 3(a), when the distance is large (e.g., 700 m), even if more repetitions would in principle increase the overall SINR thanks to MRC (as shown by the dashed curves, from left to right), the received power is mostly insufficient to detect the preamble and therefore the real improvement due to multiple transmissions is limited (solid curves). The results show that the preamble detection has a notable impact on the performance. The results in Fig. 3(b) show that the ability to detect the preamble at lower power levels can bring improved performance in the presence of retransmissions and reduce the gap from the ideal case.

B. *Setting of the Net CBR Thresholds*

The net CBR thresholds are derived by evaluating the network performance when all the vehicles adopt the same number of repetitions. In such a condition, Fig. 4 shows the *range*, defined as the maximum distance to have PRR > 0.90 varying the net CBR γ. In Fig. 4, two different propagation models are adopted to verify the generality of the derived results. In particular, in addition to the WINNER+, scenario B1 model, which is normally adopted for these kinds of studies and used in the rest of the paper, also the modified ECC Report 68 rural described in [14] is here considered. By comparing dashed and solid curves, results show that, apart from a scale factor on the distance, the impact of repetitions is similar for the two propagation models when looking at the net CBR. This means that the applicability of the derived thresholds and the performance trends that follow are not limited to the specific settings adopted in this work.

As expected, Fig. 4 confirms that in a low-load scenario the transmission of more repetitions improves the performance, whereas it has

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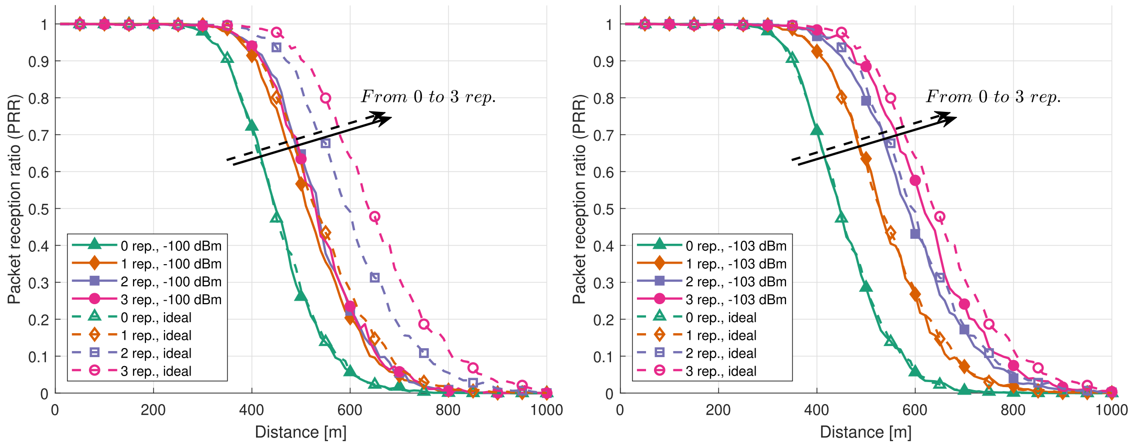
[2] The simulator is available at https://github.com/V2Xgithub/WiLabV2Xsim and the modifications will be available in future releases.

[3] In the simulator, the ideal preamble detection is modelled by setting the power level for preamble detection to the very low value of −120 dBm, which is unrealistic in practice.

TABLE I
MAIN SIMULATION PARAMETERS AND SETTINGS

Scenario	Highway, 3+3 lanes, variable vehicle density, average speed 120 km/h with 12 km/h std. deviation
Data traffic	Packets of 350 bytes generated every 100 ms
MAC settings	Maximum contention window 15, AIFS 110 μs, SIFS 32 μs
MCS	MCS 2 (QPSK, CR= 0.5), with error rate probability based on the curves in [12] (1 dB @ PER=0.5)
Rx thresholds	For preamble detection -100 dBm (except for Fig. 3), for unknown signals -65 dBm, for the CBR evaluation -85 dBm
Channel and power	Single 10 MHz channel at 5.9 GHz, tx power 23 dBm (not including antenna gain), antenna gain 3 dBi, noise figure 6 dB
Propagation	WINNER+ Scenario B1 propagation model, correlated shadowing with 3 dB variance and decorr. dist. 25 m



(a) (b)

Fig. 3. PRR vs. transmission distance for various number of repetitions, with ideal preamble detection (dashed curves) or preamble detection at the specified threshold (solid curve). Density equal to 5 veh./km. (a) Preamble detection at -100 dBm (b) Preamble detection at -103 dBm.

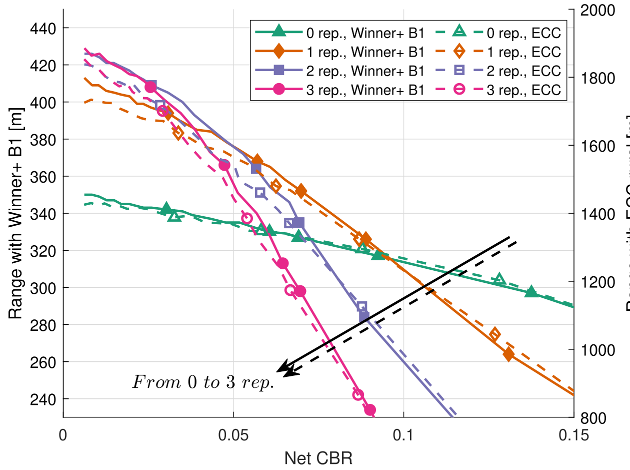


Fig. 4. Range vs. net CBR assuming different numbers of repetitions. Solid lines are derived from the WINNER+, scenario B1 propagation model and correspond to the left y-axis. Dashed lines are derived from the ECC rural model and correspond to the right y-axis.

a negative impact when the channel load is higher. For example, if we focus on the case of net CBR larger than approximately 0.09, we note that it is preferable to all stations do not use any repetitions compared to the case where all the stations transmit one repetition (the two cases have the same net CBR by definition).

Given these results and adopting the interval-setting process explained in Section III, the three thresholds are set as $\gamma_1^* = 0.09$, $\gamma_2^* = 0.05$, $\gamma_3^* = 0.03$.

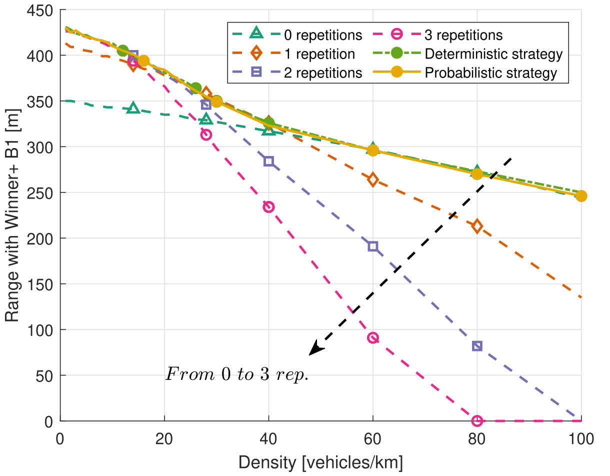


Fig. 5. Effectiveness of the repetition strategies. The dashed curves correspond to the cases where all the vehicles use the same and fixed number of repetitions. The solid curves correspond to the cases where all the stations autonomously adopt either repetition strategy.

C. Performance of the Proposed Strategies

Fig. 5 shows the range varying the vehicle density, assuming either all the stations adopt the same and fixed number of repetitions, or all the stations adopt one of the strategies detailed in Section III.[4] Please note that in the simulations the stations are completely unsynchronized and

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[4] The same simulations were also performed adopting the ECC model, leading to equivalent results.

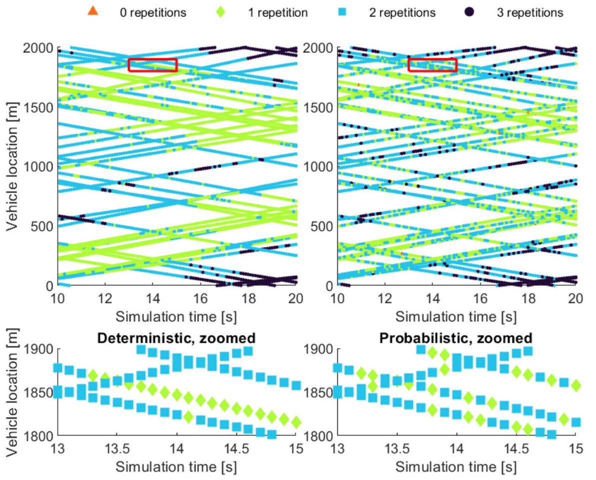

Fig. 6. Repetitions used by the vehicles in a sampled time interval plotted as a function of space and time. The two figures located lower side are zooms of the red boxes in the figures plotted upper side. Density equal to 20 veh./km.

the intervals of duration T_{CBR} used to calculate the CBR are independent among the stations. It can be noted that both the deterministic and probabilistic strategies, for any value of the density, approximately provide the same performance as the best solution with a fixed number of repetitions, therefore demonstrating the validity of the proposed approach.

Even if both strategies are effective to optimize the network performance, the probabilistic strategy allows a better distribution of the number of repetitions. This is shown in Fig. 6, which illustrates the impact of the two repetition strategies over time and space in a sample simulated interval. The two bottom-side subfigures are zooms of the upper-side ones. In each subfigure, the y-axis represents the location of the stations and the x-axis the time; the colors indicate the number of repetitions set by the station located in that position at that time. The figure shows that with the deterministic strategy the vehicles tend to maintain the same number of repetitions for longer intervals than with the probabilistic strategy; for example, looking at magnified parts in the lower subfigures, with the deterministic strategy all stations keep using 2 repetitions except a single one, which keeps using only 1 and is therefore penalized; a variable and thus fairer number of repetitions is instead selected by all stations in the probabilistic case.

The results show that both of the proposed strategies are effective to exploit the feature of repetitions with a distributed decision. At the cost of slightly higher complexity, the probabilistic strategy appears preferable, as it allows neighboring stations to transmit a similar average number of repetitions of the messages and thus improves fairness. It is also observed that the ability of the receiver to decode the preamble at low power levels is a crucial aspect to fully exploit this feature.

V. Discussion and Final Remarks

Considering the possibility added by IEEE 802.11bd to transmit more than one replica of the same packet to improve the reliability of V2X communications, in this paper we have proposed two strategies to let each station set the number of repetitions in a fully distributed way based on local measurements of the channel load, with the objective to maximize the network performance. We have validated the effectiveness of the proposed strategies through network-level simulations performed in realistic scenarios where each station autonomously performs the selection under variable conditions. The results also show the importance of correctly modelling the preamble detection phase for the design of repetition strategies and the performance evaluation. In this paper, a homogeneous scenario is considered, where a single MCS, a single traffic class, and a single channel are used; future research will explore how repetitions can be exploited under more complex scenarios.

Acknowledgment

We would like to thank the China Scholarship Council that is supporting Wu Zhuofei during his visiting scholarship at the University of Bologna.

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