PRESS: Predictive Assessment of Resource Usage for C-V2V Mode 4

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***Abstract*—Vehicle-to-Everything (V2X) communication is a key enabling factor for fully autonomous driving vehicles. To this end, the 3GPP has introduced Cellular V2X (C-V2X) standards in Release 14. For Vehicle-to-Vehicle (V2V) communication, C-V2X provides the distributed resource allocation mode, termed Mode 4, which works for sensing-based semi-persistent scheduling. However, because of the sensing-based and distributed nature, Mode 4 suffers resource collision due to congestion, channel performance degradation due to blockage, etc. Thus, making an accurate assessment of resource use in Mode 4 becomes an important issue. To address this issue, we propose a scheme for PREdictive aSSessment of resource usage in C-V2V Mode 4, named *PRESS*. In *PRESS*, each vehicle leverages aggregate reselection counter information to predict the channel usage status for future resource use. With the assessment of resource usage related to the transmission time, a VUE can increase the possibility of choosing the least used resources. Through simulation, we confirm that PRESS outperforms the legacy scheme in terms of packet reception ratio.**

I. INTRODUCTION

Recently, a variety of approaches for fully automated driving have been actively pursued. On the autonomous driving side, advanced sensor and vision processing technology is growing rapidly. With such technologies, vehicles are enabled to detect objects such as pedestrians and vehicles, and build autonomous driving strategies based on the detection results. These approaches promise a bright future, but the existence of blind spots in the Non-Line-of-Sight (NLOS) section is an inherent limitation. A connected car approach, where vehicles share information through vehicle-to-vehicle (V2V) communication, can overcome this limitation. Through information sharing, vehicles can benefit from a richer and more collective cognition. Thus, vehicles can reduce the likelihood of accidents.

To this end, the European Telecommunications Standards Institute (ETSI) specified an approach using Cooperative Awareness Message (CAM) [7], where a vehicular UE (VUE) notifies its status to neighboring VUEs by periodically broadcasting its speed, direction, etc. To exchange such safety messages in vehicular networks, the 3GPP has standardized Cellular-Vehicle to Everything (C-V2X) communication in release 14 [1]. C-V2X provides two resource allocation modes: Mode 3 and Mode 4. Mode 3 is a centralized scheduling scheme that uses the eNB as the subject of resource allocation. The eNB allocates resources for VUEs by taking channel usage status into account.

On the other hand, Mode 4 is a decentralized scheme that uses VUEs as the subject of resource allocation. Each VUE tries best to find the optimal resource for transmission by estimating the channel usage status with the sensed data. The approach in Mode 4 can be simply defined as a sensing-based Semi-Persistent Scheduling scheme (SPS). It chooses the resource to be used for transmission based on Sidelink Received Signal Strength Indicator (S-RSSI). Once chosen, the VUE exploits the resource for transmission for a certain number of times in a row, which is the Reselection Counter (RC).

Although the sensing-based SPS is a simple yet powerful approach, it has some limitations. Due to the fixed sensing window, polluted information may be included in the sensing window. In other words, the sensing window may include information from outdated transmissions. Because of this, the resource usage assessment results in irrelevant to actual resource use for transmission. This problem may seem unavoidable, but it is worth noting that CAMs are transmitted periodically. Due to the periodicity of CAM, resource usage assessment has room for more predictability, which has not been studied.

To this end, we design *PRESS*, a scheme for predictive assessment of resource usage in C-V2V Mode 4. *PRESS* utilizes the predicted channel usage status for resource assessment. With a more relevant assessment of resource usage along with the resource use time for transmission, VUEs benefit from the increased possibility of choosing the least used resources.

The contributions of this paper are as follows:

- We point out the limitations of resource assessment in the legacy scheme in terms of a newly defined metric, called Matching Ratio (MR).
- We propose a scheme for predictive assessment of resources for C-V2V Mode 4, termed *PRESS*, that is standard compliant.
- We evaluate the performance of *PRESS* in crossroad and highway scenarios via system-level simulation.

The rest of this paper is organized as follows. We first present the related work in Section II and introduce the preliminaries for this paper in Section III. Section IV describes the design of *PRESS* in detail. Then, we investigate the performance of *PRESS* in Section V. Finally, we conclude our paper in Section VI.

II. Related Work

There have been several works tackling the inherent problems of C-V2V Mode 4 to enhance its performance. To address the limitation of Half-Duplex (HD) transmission, Campolo *et al.* test out the potential of full-duplex transmission for C-V2X [5]. As a measure to deal with the famous hidden-terminal problem, alternative approaches propose the use of geographical information based scheduling [10], [12]. While these works open up new possibilities, discrepancies with the standard are obstacles for practical application.

Several works tackle the resource collision problem due to congestion and try to alleviate and coordinate collision among VUEs. Without this coordination, sensing-based SPS can result in VUEs choosing the identical resource for transmission. The legacy scheme, Mode 4 utilizes random selection among the best candidate resource list to alleviate resource collision. Jeon *et al.* proposed reservation-based collision coordination among the vehicles allocating resource simultaneously [9]. Saif Sabeeh *et al.* proposed a resource allocation method where VUEs with the same reselection counter share the resource pool and coordinates collision [11]. Bonjorn *et al.* proposed a potential packet collision avoidance scheme by modifying the RC value [4].

On the other hand, we believe that the correct assessment of resource usage is another problem worth addressing. From this point on, we abbreviate the phrase, assessment of resource usage as ARU. Without a proper ARU, the benefit of coordination between resources collision would be limited. To the best of our knowledge, only a few works address this issue. Mis-assessment of resources can occur due to several reasons, such as congested environment, dynamic topology change, and irrelevant information included in the sensing window, etc. Hirai and Murase address that sensing-based SPS may fail at choosing the desirable resource due to heavy congestion [8]. Due to mis-assessment of resources, performance may degrade even comparable to a random allocation scheme. Abanto-Leon *et al.* proposed an intuitive weighting approach to impose heavier weight to more recently sensed values [3]. This allows the ARU to be more up-to-date, suppressing the effect of irrelevant, polluted information.

We believe that by exploiting the RC information for each resource more collectively, we can obtain a precise sensing window, sifting out all irrelevant information. Additionally, we exploit the periodicity of CAM to obtain a predictive ARU of each resource, expected to be relevant with the VUE's actual resource exploitation time.

III. Preliminary

In this section, we provide an explanation of C-V2V Mode 4 and the motivation of this work.

A. Sensing-based Semi-persistent Scheduling for C-V2V Mode 4

Fig. 1 illustrates the resource grid of the sidelink channel, used for C-V2V. The minimum unit in time for the grid is one subframe (1 ms) and one sub-channel in frequency (180 kHz). From this point on, we phrase the group of adjacent sub-channels within the same sub-frame where the Sidelink Control Information (SCI) and data can fit in as just 'resource.' Mode 4 is an autonomous and decentralized resource scheduling scheme that does not require the assist of cellular infrastructure. In Mode 4, the VUE continuously senses the channel for Sidelink Received Signal Strength Indicator (S-RSSI) of each resource. The S-RSSI within the sensing window is utilized for resource allocation. The length of the sensing window is fixed to 10 Transmission Time Interval (TTI). Since the TTI is set as 1000 ms by default for CAM, the default sensing window length is 1000 ms.

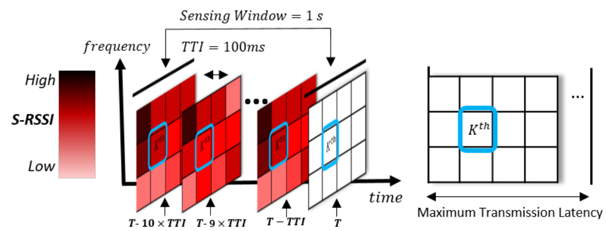


Fig. 1. C-V2V Mode 4.

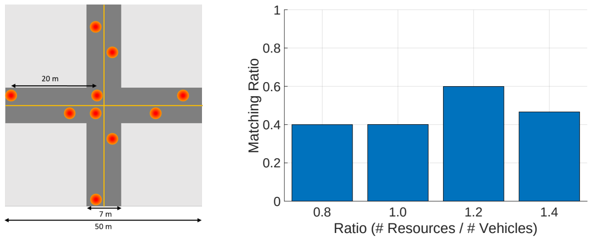
Once a VUE selects a resource, the VUE utilizes it for transmission for a certain number of times in a row. This number is the Reselection Counter (RC) and is chosen randomly between 5 and 15, for when TTI is 100 ms. Every time VUE transmits a message, RC is decreased by one. Once it reaches zero, VUE will go into the resource reselection phase with probability $1 - P_{keep}$. P_{keep} is a configurable parameter between zero and 0.8. In this work, we set P_{keep} as 0.

Mode 4's resource allocation procedure can be split into three steps. At the initial stage of the resource (re)selection process, VUE defines the total list of resources. If a VUE is reserving a new resource at time t, the total list of resources is defined between t and ($t+$ Maximum transmission latency).

Step 1: Unusable Resource Exclusion: Among the total list of resources, 'unusable resources' are excluded. Two conditions define whether a resource is unusable. The first condition is whether any transmission is known to be scheduled in the resource when VUE will need to exploit it for transmission. In other words, whether any more transmissions are scheduled according to the decoded SCI received at the resource. The second condition is whether the average value of the sensed Reference Signal Received Power (RSRP) of the resource within the sensing window exceeds a predefined threshold. If a resource meets both conditions, it is marked as 'unusable.'

Additional to the unusable resources, resource in the same subframe with the resource VUE has previously used for transmission is also excluded. This is because sensing information was not obtainable due to HD transmissions. If the number of usable resources after the exclusion step is less than 20% of the number of the total list of resources, the threshold in the second condition is increased by 3 dB iteratively until the number of the usable resource is at least 20% of the total.

Step 2: Best Resource List Generation: After excluding the unusable resources, VUE sorts the resource according to



(a) Topology (b) Matching Ratio

Fig. 2. Motivational Study.

the average RSSI value measured over the sensing window. From the sorted list, 20% of resources with the smallest average RSSI value are chosen.

Step 3: Resource Selection: Among the chosen list, a resource is randomly selected. Due to this randomizing step, VUEs in the vicinity become less likely to choose the same resource.

B. Problem and Motivation

We now point out the limitations of the legacy scheme, C-V2V Mode 4, specifically the ARU performance. As the ARU performance is shaded by random resource selection, to directly measure the ARU performance, we define a metric named Matching Ratio (MR).

Before defining MR, we first explain the oracle scheme, the basis for computing MR. The oracle scheme is the optimal resource selection scheme with respect to the system Packet Reception Ratio (PRR). The scheme first computes the system PRR for all the resources supposing that according resource has been exploited for the next transmission, denoted as PRR. After sorting with respect to the resulting system PRR, the best resource list is drawn. The cardinality of the best resource list drawn from the oracle scheme is the same as the one drawn by Mode 4. We name the resource which gives out the worst system PRR among the best resource list as $Worst_{Oracle}$. In short, the oracle scheme selects the resources with minimal usage for the very next transmission time. MR is the ratio of which best resource list drawn from a resource allocation scheme qualifies compared to that drawn from the oracle scheme. Firstly, we check the system PRRs from the transmissions exploiting the resource from the best resource lists drawn by Mode 4. Then, only the resources that give out higher system PRR than $PRR(Worst_{Oracle})$ are counted as 'matching.' In short, MR result measures how capable a resource allocation scheme is at assessing the resource with minimal usage for the very next transmission. MR of resource allocation $schemeA$ is defined by the equation below.

$$MR(A) = \frac{\sum_{x \in L_{Best}(A)} I(x)}{|L_{Best}(A)|}$$

$$I(x) := \begin{cases} 1, & \text{if } PRR(x) \geq PRR(Worst_{Oracle}) \\ 0, & \text{otherwise} \end{cases}$$

To focus the observation only on the ARU performance, we choose a simple scenario. Fig. 2(a) is the topology for motivational study. 10 Vehicles are placed at a cross-shaped road with a fixed position. Buildings at the corners provide an NLOS path between the VUEs. With the number of vehicles fixed, the number of resources is modified to illustrate various congestion levels. The X-axis of Fig. 2(b) is the ratio between the number of resources & vehicles. For example, the environment with a ratio of 0.8 is when for 10 vehicles, there are only 8 usable resources. This environment illustrates an extremely congested scenario, with inevitable collisions. Fig. 2(b) shows that Mode 4 outputs a low matching ratio of below 0.5 on average. This result implies that Mode 4 falls short at assessing the resource usage status for the next transmission. Since the environment is static, we can conclude that this mis-assessment of resource usage results from the out-dated information included in the sensing window.

IV. Proposed Scheme: *PRESS*

Our motivational study shows that ARU in Mode 4 falls short at assessing the least used resources for the actual transmission time. In this section, we present the design of *PRESS*, which addresses the shortcomings of the legacy scheme. *PRESS* is a scheme that provides a predictive assessment of channel usage by exploiting the periodic nature of CAM. It takes into account not only the signal strength of transmissions but also the number of scheduled transmission left in the assessment.

A. Overview

Fig. 3 illustrates the overview of the resource selection procedures in *PRESS*. For simplicity, we explain *PRESS* in the context of resource (re)selection phase of VUE k at time t. Firstly, VUE k chooses the new reselection counter (RC^k_{New}). Then, *PRESS* predicts the channel usage status upon the time of resource exploitation, in $[t, t{+}RC{\times}TTI]$. VUE k executes unusable resource exclusion and best resource list generation utilizing this predicted channel usage.

For prediction, VUE k needs the information of the transmissions which were not received. This is because if the transmission in a certain resource had been received and decoded successfully, it is highly probable that the resource has already been excluded as unusable. VUE k obtains information of non-received transmissions from its neighbors whose set is denoted as N_k. Each VUE sends the RC value for each resource known to itself by decoding the SCI. Then each VUE obtains an aggregate RC status for each resource. VUEs can notice the existence of non-received transmissions from the discrepancy among the RC values. To avoid the excessive signaling overhead, the reserved field in the SCI can be utilized.[1]

PRESS consists of two parts: signal strength estimation and RC application. The first part estimates the signal strength of transmissions present at resource (re)selection time, t.

[1]For SCI format 1 utilized in Mode 4, 13 bits remain as the zero-padded reserved field, when the size of CAM is 300 bytes, and MCS level is under 7 [1].

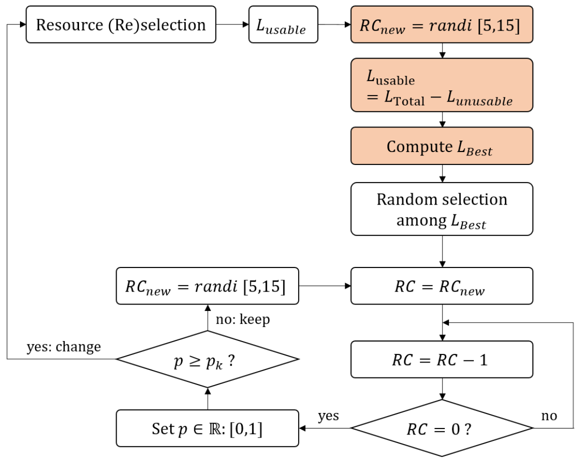


Fig. 3. Flow Chart of *PRESS*. White boxes represent the legacy Mode 4 operation and colored boxes are the proposed modifications.

To obtain the exact estimate, *PRESS* sifts out the out-dated information in the sensing window. The second part applies the number of scheduled transmissions left to the estimated signal strength. In other words, the present RC of each transmission is applied to the estimated signal strength. In this way, *PRESS* takes into account the expected effect of transmission upon the resource exploitation time. Let's look into each part in detail.

B. Signal Strength Estimation

To sift out the outdated information and only consider the transmissions present at time t, VUE k needs to know the starting point of each transmission. *PRESS* obtains this information by backtracking the RC decrement. If the RC value would not decrease by one every TTI, it implies another transmission. RC decrement is accumulated until the RC discontinuity. By utilizing the RC decrement, VUE k sift out all the irrelevant information by limiting the start point of the sensing window. Algorithm 1 shows the signal strength estimation part in *PRESS*.

Algorithm 1 *PRESS*: Signal Strength Estimation

Input:

- TTI ▷ Transmission time interval of CAM
- $RC^k_{pres}(n)$ ▷ Present reselection counter for transmission in n_{th} resource known to VUE k
- $RC^{N_k}_{pres}(n)$ ▷ Set of present reselection counters for transmission in n_{th} resource according to neighbors of VUE k
- $RC^k_{dec}(n)$ ▷ Set of RC decrement for transmission in n_{th} resource known to VUE k
- $RC^{N_k}_{dec}(n)$ ▷ Set of RC decrement for transmission in n_{th} resource according to neighbors of VUE k
- $RSSI^k(t)$ ▷ S-RSSI values sensed by VUE k at time t

Output:

- $S^k(n)$ ▷ Signal Strength estimate of n_{th} resource by VUE k

1: **for all** $j \in Resources$ **do**
2: **if** $RC_k(j) > 0$ **then**
3: $RC_{dec} = min[RC^k_{dec}(j), RC^{N_k}_{dec}(j)]$
4: $S^k(j) = \frac{1}{RC_{dec}} \sum_{i=1}^{RC_{dec}} RSSI(t - i \times TTI)$
5: **else**
6: **if** $\exists\ x \in RC^{N_k}_{pres}(j)\ s.t.\ x \neq RC^k_{pres}(j)$ **then**:
7: $RC_{dec} = min[RC^{N_k}_{dec}(j)]$
8: $S^k(j) = \frac{1}{RC_{dec}} \sum_{i=1}^{RC_{dec}} RSSI(t - i \times TTI)$
9: **else**:
10: $S^k(j) = 0$
return S^k

- *(line # 2 - 6)*: Whether VUE k received any transmission in the resource (line # 2 - 3) or not (line # 4 - 6), these cases imply that there exist one or more present transmissions. To sift out all the irrelevant information and consider only the present transmissions, we limit the start of the sensing window to the latest starting point among all the present transmissions.
- *(line # 7 - 8)*: This case implies that VUE k and all of its neighbors reach the consensus that there is no transmission present on this resource. Thus, it is safe to say that this resource has minimal usage. Even if this resource were not sensed due to HD transmission, VUE k could consider this resource as a resource with minimal usage.

C. RC Application

To additionally consider the lasting transmission effect, we multiply the estimated signal strength by the present RC of each transmission. Since we are only interested in the channel usage status of a resource when the VUE exploits it, we take a minimum operation on the present RC with RC^k_{new} and divide by it. Algorithm 2 shows the RC application part in *PRESS*.

- *(line # 2 - 3)*: $RC_k(j) > 0$ implies that VUE k has received messages in the jth resource, and has yet to receive in the future. We mainly consider the effect of the received transmission since the signal strength of the received transmission is dominant. Otherwise, it wouldn't have been successfully received. We apply the present RC of the received transmission to the estimated signal strength.
- *(line # 5 - 6)*: The discrepancy between RC values implies that either a collision occurred or the transmission's signal to noise ratio (SNR) is too low. For the case of collision, we estimate the signal strength of each colliding transmissions as equal. This estimation grounds on the fact that for the occurrence of collision, no transmission is dominant in power. Otherwise, VUE k would have received transmission through capture effect. Since the number of different present RC values implies the number of colliding transmissions, we estimate the signal strength of each colliding transmission as $(\frac{S^k_{(j)}}{|RC^{N_k}_{pres}(j)|})$. We apply the present RC according to neighbors, $RC^{N_k}_{pres}(j)$, to the estimated signal strength. Then we sum up the effect of each transmission. For the case of low SNR, it is trivial because the signal strength would be

Algorithm 2 *PRESS*: RC Application

Input:

$S^k(n)$ ▷ Signal strength estimate of n_{th} resource by VUE k

RC^k_{new} ▷ Newly chosen reselection counter by VUE k

$RC^k_{pres}(n)$ ▷ Present RC for transmission in n_{th} resource known to VUE k

$RC^{N_k}_{pres}$ ▷ Set of present RC for transmissions in n_{th} resource according to neighbors of VUE k

Output:

$P^k(n)$ ▷ Predictive assessment of n_{th} resource by VUE k

for all $j \in Resources$ **do**
  if $RC^k_{pres}(j) > 0$ **then**
    $P^k(j) = S^k_{(j)} \times \frac{min[RC^k_{pres}(j), RC^k_{new}]}{RC^k_{new}}$
  else:
    if $\exists\ x \in RC^{N_k}_{pres}(j)\ s.t.\ x \neq RC^k_{pres}(j)$ **then**:
      $P^k(j) = \frac{S^k_{(j)}}{|RC^{N_k}_{pres}(j)|} \times \sum \frac{min[(RC^{N_k}_{pres}(j)), RC_{new}]}{RC_{new}}$
    else:
      $P^k(j) = 0$
return P^k

negligible.

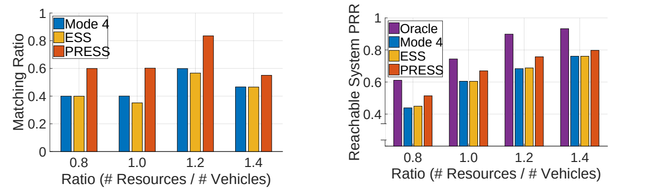
Through considering each case, *PRESS* obtains ARU more relevant to the time of resource exploitation for transmission.

V. Evaluation

A. Simulation Setup

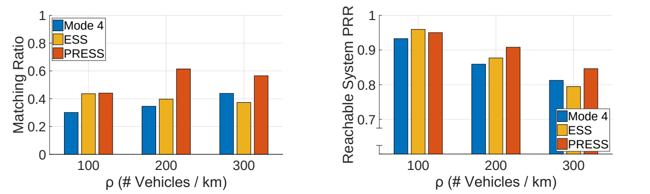
For evaluation, we use MATLAB simulator based on LTEV2Vsim [6]. We evaluate *PRESS's* performance compared to Mode 4 and ESS [3]. Mode 4 is the legacy scheme standardized by 3GPP, and ESS is the scheme proposed in [3]. It is the abbreviation of the first three words from the title of the paper, 'Enhanced Subchannel Selection.' This scheme applies exponentially decaying weight to impose heavier weight to the more recent RSSI measurements within the sensing window. For MCS, index 7 is used according to table 8.6.1-1 in 3GPP TS 36.321 [2]. More simulation settings are described in Table I.

To validate the performance gain of *PRESS*, we choose 2 scenarios. Firstly, to validate the enhancement on the issue pointed out in the motivational study, we use the same topology, the crossroad scenario. Then, we evaluate it on a straight road highway scenario with varying vehicle density, ρ. ρ signifies the number of vehicles per km. Each density, ρ : $\{150, 250, 350\}$, corresponds to the average number of neighbors of $\{43, 73, 101\}$, respectively. The speed of the vehicles follows a normal distribution with a mean and standard deviation of 114 km/h, 12.7 km/h. The following metrics are used to evaluate the performance of *PRESS*.



(a) Matching Ratio (b) PRR

Fig. 4. Crossroad Scenario.



(a) Matching Ratio (b) PRR

Fig. 5. Highway Scenario.

TABLE I
Simulation Settings

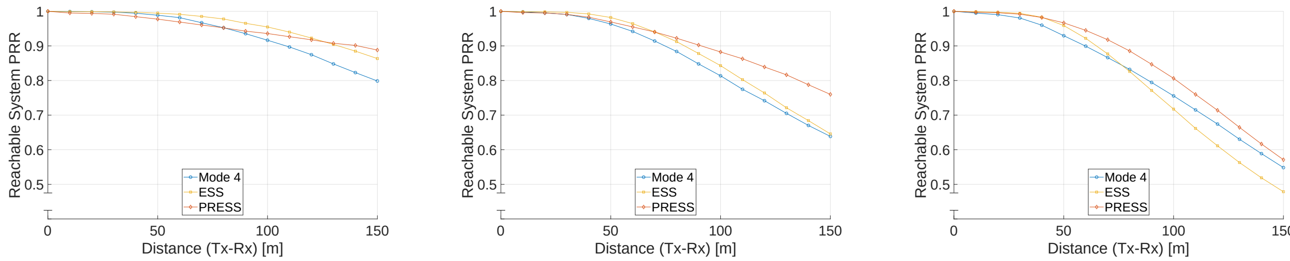
Parameter	Crossroad	Highway
Map Size	50 m × 50 m	4km (3 lanes / direction)
CAM size	300 bytes	
Bandwidth	10 MHz	
Antenna gain	3 dB	
Propagation model	WINNER+, Scenario B1	
Shadowing variance	3 dB (LOS), 4 dB (NLOS)	
Required minimum SINR	7.30 dB (MCS 7)	

- **Matching Ratio (*MR*)** reflects the capability of a resource allocation scheme at assessing the resource with minimal usage at the next transmission time.
- **Reachable System PRR** is the average ratio of correctly received CAMs over the total number of transmitted. To measure the resource usage assessment capability more directly, we alleviate the effect of collision. We keep the VUEs entering the resource (re)selection phase simultaneously away from choosing the same resource.

B. Simulation Results

1) Crossroad: Fig. 4(a) shows the MR performance in the crossroad scenario. The X-axis is the ratio between the number of vehicles and the number of resources, illustrating an extremely congested scenario (0.8) to a relatively sparse scenario (1.4). Firstly, we can observe that *PRESS* obtains higher MR for all the ratios. However, for the most sparse case (1.4), we can observe the decrease in MR gain. This is because for the case where many resources have minimal usage, deciding which one to choose among them becomes very subtle. As shown in Fig. 4(b) 0.8, although the capability to choose the 'optimal' resource is decreased, the reachable system PRR shows increase.

Additionally, we can observe some counter-intuitive results between ESS and legacy. Although ESS's approach seems reasonable, some cases show MR decrease for ESS compared to the legacy. We interpret this result as due to the lack of the averaging effect. In other words, although the RSSI is a



(a) ρ = 150 (b) ρ = 250 (c) ρ = 350

Fig. 6. Reachable System PRR VS. Distance between the transmitting VUE and the receiving VUE

measurement with fluctuation, exponential decay makes only the recent measures to stand out. On the other hand, *PRESS* takes advantage of the averaging effect within the relevant range of the sensing window.

Overall, *PRESS* outperforms the compared schemes in terms of MR by over 18% on average. Although MR gain doesn't directly result in reachable system PRR gain due to the randomizing process, the enhanced ability to assess the resource with minimal usage uplifts the possibility of a VUE choosing the optimal resource. Accordingly, the reachable system PRR in Fig. 4(b) also shows increase, up to 7%.

2) Highway: Fig. 5(a) shows the MR performance gain in the highway scenario. Similar to the crossroad scenario, MR gain is minimal for a very sparse environment ($\rho = 100$). We can even observe a small decrease in the reachable system PRR ($< 1\%$) compared to ESS. This result can be interpreted as a case where although MR is the same, random resource selection leading to the choice of the resource with more usage. However, as the scenario gets denser ($\rho = 200, 300$), and as the RC information to be utilized for *PRESS* increases, we can observe the MR gain. Thus, resulting in the reachable system PRR improvement as shown in Fig. 5(b). Reachable system PRR increases up to 5% for the $\rho = 200$ case.

Fig. 6 shows the PRR performance against the distance between the transmitting VUE and the receiving VUE for the highway scenario. We can see PRR gain at mid-range distance. This is due to starting at mid-range, VUEs start receiving information about concurrent, but not received transmissions. Thus, neighbors at the mid-range can benefit from the collective RC information of *PRESS*.

VI. Conclusion and Future Work

In this paper, we tackled the problem of resource usage assessment for C-V2V Mode 4. Then, we introduced *PRESS*, a scheme for predictive assessment of resource usage for C-V2V Mode 4, to overcome the limitations of the legacy scheme in terms of the matching ratio. *PRESS* exploits the periodicity of CAM to estimate future resource usage status at the time of resource use. Through simulation, we confirmed that the enhanced capability of *PRESS* in assessing the minimally used resource leads to a higher possibility of choosing the optimal resource in future transmission. We leave the development of a resource assessment scheme taking into account vehicular mobility additionally as future work.

Acknowledgment

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