SnB: Reduction of Consecutive Message Reception Failures in C-V2X Communications

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***Abstract*—Cellular vehicle-to-everything (C-V2X) features have been standardized in 3GPP Release 14. In particular, the standard introduces a fully-distributed resource-allocation algorithm for Mode 4 configuration, called *sensing-based semi-persistent scheduling* (SB-SPS). Although SB-SPS is effective for orthogonal radio resource allocation, it could easily suffer consecutive message losses caused by interference or half-duplex transmission since SB-SPS uses a selected resource consecutively (multiple times) for periodic transmissions. To mitigate this problem, we propose a novel Mode 4 resource-allocation algorithm, called SnB (Shake-and-Back). Instead of using a selected resource consecutively, SnB either randomly selects and uses a resource each time or uses a selected resource based on its decoding state to avoid consecutive message losses. We have conducted extensive simulations using NS-3 to evaluate SnB considering its coexistence with SB-SPS. Our evaluation results show that SnB improves the average message reception ratio (MRR) at three or more consecutive message losses significantly.**

I. Introduction

Full autonomous driving is expected to drastically change our society and life style. The full autonomous driving will heavily rely on vehicle-to-everything (V2X) wireless communication to obtain the comprehensive recognition of surroundings. Nowadays, Cellular V2X (C-V2X) features standardized by 3GPP are regarded as the most promising technologies for the V2X wireless communication.

Because C-V2X adopts single-carrier frequency division multiple access (SC-FDMA), orthogonal allocation of radio resources to vehicles is very important to avoid *resource collision*[1]. For the resource allocation, 3GPP Release 14 defines Modes 3 and 4. In Mode 3 configuration, given radio resources are managed and allocated to vehicles by eNodeB (eNB), so one can expect that given radio resources are well allocated to vehicles. On the other hand, in Mode 4 configuration, each vehicle selects a radio resource for its transmission without any centralized coordination/assistance, so each vehicle should be equipped with a fully-distributed resource-selection algorithm.

For the Mode4 configuration, 3GPP has standardized a fully-distributed resource-selection algorithm, called *sensing-based semi-persistent scheduling* (SB-SPS). To avoid resource collision, SB-SPS estimates contention-free resources (i) by exploiting the distinct characteristic of *semi-persistent scheduling* (SPS) under which a selected resource is used consecutively for periodic transmissions, and (ii) by sensing signal power on each radio resource. For example, when high power is sensed on a resource, we can infer that the resource is being used by neighbor vehicles, and thus it would be used again for the next transmission. However, because SB-SPS selects a selected resource consecutively for periodic transmissions (characteristic of SPS), when a message reception failure happens, consecutive message reception failures (CMRFs) would happen.

[1]A resource collision occurs when two or more vehicles select a same radio resource for their transmission, and thus transmitted messages cannot be delivered to the receivers correctly due to the interference.

To mitigate CMRFs problem, we propose a novel Mode 4 fully-distributed resource-selection algorithm, called SnB (`Shake and Back`). SnB is designed with consideration of its coexistence with the standardized algorithm, SB-SPS, because it is practically impossible for every vehicle to adopt SnB instead of the standardized algorithm. In other words, SnB should be aware of, and exploit the characteristic of SB-SPS to avoid the degradation/failure of communication performance. Therefore, SnB retains and exploits SPS to estimate contention-free resources, but resolves the problem of CMRFs. SnB consists of two phases. In the first phase, SnB tries to select a contention-free resource based on the average signal power on each resource. In the second phase, SnB attempts to resolve CMRFs by randomly selecting a resource which has a relatively high average signal power (**Shake**). Since use of a random resource makes it difficult to identify contention-free resources in the first phase, SnB intentionally re-selects the originally-selected resource in the first phase if there is no decoded signal on the originally-selected resource to raise the average reference signal received power (RSRP) of the originally-selected resource (**Back**).

SnB is evaluated via extensive simulation using ns-3. Our evaluation results show that SnB improves the average message reception ratio (MRR) by 253% at 3 consecutive misses and by 552% at 5 or more consecutive misses. Also, our in-depth simulation shows that SnB enhances the entire communication performance with its coexistence with SB-SPS.

II. Related Work

Enhancements of SB-SPS have been proposed. Molina-Masegosa *et al.* [9] only applied the reservation count to resource reservation for frequent small packets for efficient use of resources. Because a vehicle cannot know whether the transmitted signal is jammed with by other signals or not, Park *et al.* [10] added the feedback-aided resource-changing decision to SB-SPS. Jeon *et al.* [7] and Bonjorn *et al.* [5] reduced the probability of resource collision by sending additional information such as future resource reservation or the remaining reservation count. L. F. Abanto-Leon *et al.* [4] applies non-linear weight to the recently measured power on each resources instead of applying same weight.

Instead of enhancing SB-SPS, different ways of resource selection algorithm for Mode 4 also have been proposed. Cecchini *et al.* [6] utilizes decoding state map to select a resource instead of RSRP to improve MRR. Sahin *et al.* [13, 14] proposed a method of resource pre-assignment by eNB before entering an out-of-coverage area for a tunnel-like scenario.

Although these studies show better performance than the standard SB-SPS algorithm, they suffer the following problems. First, the studies in [5, 6, 7, 9, 10, 13, 14] assume that all the vehicles would use their non-standard algorithms. This is unrealistic because there exist various car manufacturers (Hyundai, GM, etc.) and communication chip makers (Samsung, Qualcomm, etc.). Assuming certain percentages of vehicles with SB-SPS is more realistic. Second, in that sense, appending additional information [5, 6, 7, 10] on SCI or TB is also impractical because there is no agreement between vehicles using SB-SPS and vehicles using non-standardized ones. Third, some algorithms [13, 14] are designed for special conditions such as delimited out-of-coverage area. Finally, these studies have not addressed the problem of CMRFs to improve reliability in communication. In this paper, we develop an algorithm accounts for both the coexistence of SB-SPS and CMRFs which have not been considered before.

III. Background

C-V2X adopts SC-FDMA. Thus, a vehicle uses two-dimensional time-frequency radio resources for transmission. The minimum unit of radio resource that can be allocated to a vehicle for transmission is a *resource block* (RB) pair, 180kHz bandwidth in frequency and 1ms duration in time (14 SC-FDMA symbols). The 1ms duration is the minimum time unit for message scheduling, and called a *subframe* or *transmission time interval* (TTI). C-V2X is expected to operate in 5.9GHz band for intelligent transportation system (ITS) with 10MHz (or 20MHz) channel bandwidth. The 10MHz channel bandwidth is further divided into *sub-channels*. A sub-channel is composed of multiple consecutive physical RBs (PRB). The number of RBs in a sub-channel can vary, and it is usually configured by considering the size of data to be transmitted.

A. 3GPP Mode 4 resource allocation [1]

Since each vehicle is expected to periodically broadcast *Cooperative Awareness Message* (CAM) [3] for V2X services, SB-SPS algorithm reserves a selected resource multiple times for these periodic transmissions in a semi-persistent manner as shown in Fig. 1. In the context of SB-SPS, at every t_{mb}, radio resources are given in the form of a $N_{sch} \times (T_2 - T_1 + 1)$ matrix where t_{mb} is the message broadcast period, N_{sch} is the number of sub-channels in a subframe, and T_1 $(1 \leq T_1 \leq 4)$ and T_2 $(20 \leq T_2 \leq 100)$ are the given parameters for SB-SPS as shown in Fig. 1. Note that T_2 is usually consistent with the message period and a cell/entry in the matrix represents a time-frequency resource.

To transmit a data packet, each vehicle should select one or multiple contiguous resources in a subframe. When resources are selected, SB-SPS uses the resources repetitively for a certain amount of time. The range of the number of repetitions (Cnt_{rsv}) is determined based on t_{mb} (e.g., $Cnt_{rsv} \in [5, 15]$ if $t_{mb} = 100ms$), and random value is chosen within the range. The Cnt_{rsv} is decremented by 1 for every transmission. When Cnt_{rsv} becomes 0, new resources are selected with the pre-configured resource re-selection probability p_k $(20 \leq p_k \leq$

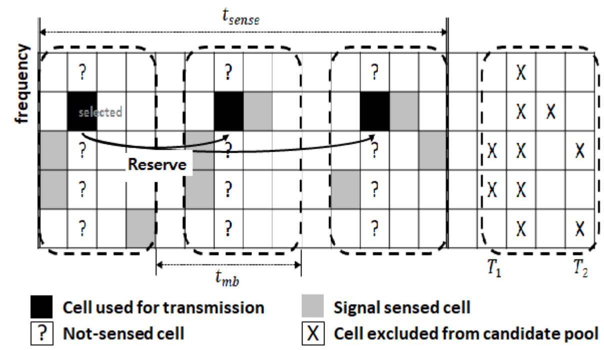

Fig. 1. Sensing-based semi-persistent scheduling ($T_1 = 2, T_2 = 5$)

$100)$ and the reservation count (Cnt_{rsv}) is randomly chosen again. If the re-selection does not proceed with the probability $(1 - p_k)$, then previously-selected resources are kept with the newly determined reservation count.

To select a contention-free resource, SB-SPS relies on the recent past signal sensing history when it selects a new resource for transmission. Because a selected resource is used multiple times under SB-SPS, we can infer that vehicles will likely keep using the same resource in the near future. Hence, it is effective to select infrequently-used resources as contention-free resources. To select the contention-free resources, SB-SPS senses signal power on each resource for the last t_{sense} milliseconds (sensing window) and creates a resource candidate pool based on the sensing result.

Initially, all the given resources are put into the resource candidate pool, and then SB-SPS excludes all the resources which are in the not-sensed subframes from the resource candidate pool. Note that a vehicle cannot receive any signal when it transmits due to the half-duplex characteristic of physical layer. SB-SPS then excludes the resources which have higher average RSRP than a specified threshold from the resource candidate pool. After the exclusion process, if the number of remaining resources in the resource candidate pool is smaller than N_r $(= N_{sch} \times (T_2 - T_1 + 1) \times 0.2)$, SB-SPS increases the threshold by 3dBm and executes the exclusion procedure again until the number of remaining resources is larger than N_r. After that, the remaining resources in the resource candidate pool are sorted by the average sidelink-received signal strength indicator (S-RSSI). From the sorted pool, only those N_r resources with low S-RSSI are chosen as the final candidates, and a resource is selected randomly from the final pool of candidates for future transmission.

IV. System Model and Goal

A. System Model

We consider V2V communication based on 3GPP Release 14 Mode 4 configuration in which vehicles communicate directly with each other using PC5 interface without any centralized assistance from eNBs.

We assume that every vehicle uses the same broadcast period t_{mb} (e.g., 100ms[3]) and broadcasts the same 300byte CAM [3] using a channel of 10MHZ bandwidth in 5.9GHz ITS band. We assume that the shared radio resources are given in the form of $N_{sch} \times t_{mb}$ every t_{mb} to a vehicle where N_{sch}

is the number of sub-channels in a subframe. We will use the term 'round' for the time duration of t_{mb}. A Cell/entry in the matrix represents a resource which is defined as $r_{sch,sf}$ where sch is the sub-channel index and sf is the subframe index. The resources with different sub-channel or subframe indices are orthogonal to each other. A vehicle selects and uses a resource for its transmission.

We also assume that some automotive manufacturers adopt the standardized SB-SPS algorithm for Mode 4 configuration, so SNB should work under its coexistence with SB-SPS.

B. Analysis of SB-SPS and Our Goal

SB-SPS selects a contention-free resource well, but SB-SPS could easily cause CMRFs. Suppose two vehicles broadcast messages periodically using the same period (e.g, 100ms), and the vehicles select $r_{1,1}$ to broadcast their own messages. The signals from the vehicles would interfere with each other, and thus the messages would not be delivered correctly to their receivers/neighbors. Because the vehicles use $r_{1,1}$ repetitively for their next transmissions, the receivers/neighbors would experience CMRFs. The CMRFs also happen between two vehicles when they use the same subframe for their transmissions due to the half-duplex problem.

We have measured MRR at different number of CMRFs to see how SB-SPS affects the message loss pattern via simulation. The details of simulation configuration will be provided in Section VI. The results are plotted in Fig. 2, showing that MRR at 0 or 1 message loss is similar to the average MRR, but MRR at 2 or more CMRFs are significantly lower than the average MRR. For example, MRR drops by about 66% (from 76% at 0 loss to 10% at 5 or more CMRFs). If CMRFs are mainly caused by the weak signal, MRR at any number of CMRFs should be similar to the average MRR. Thus, the results show that CMRFs are mainly due to the poor resource selection of SB-SPS.

Thus, our goal is providing a Mode 4 resource-selection algorithm which minimizes the problem of CMRFs under its coexsitence with SB-SPS.

V. PROPOSED ALGORITHM: SNB

A. Overall Flow of SNB

In this section, we propose a new fully-distributed resource selection algorithm for Mode 4, called SNB (Shake and Back). The overall flow of SNB is depicted in the Fig. 3. Like SB-SPS, SNB also uses the concept of SPS. So, SNB also has the reservation count (Cnt_{rsv}) as a parameter. If the reservation count is 0, then SNB executes Phase 1 procedure which selects a new resource for transmission and assigns a new value to the resource reservation counter. Otherwise, SNB executes Phase 2 procedure and decrements the resource reservation count by 1. We will see details of Phase 1 and Phase 2 procedures.

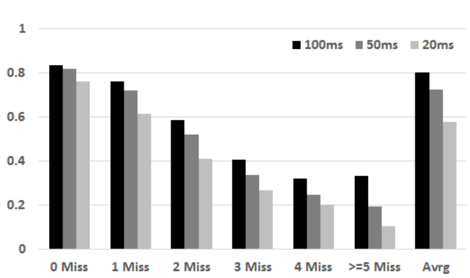

Fig. 2. Average MRR at different number of CMRFs

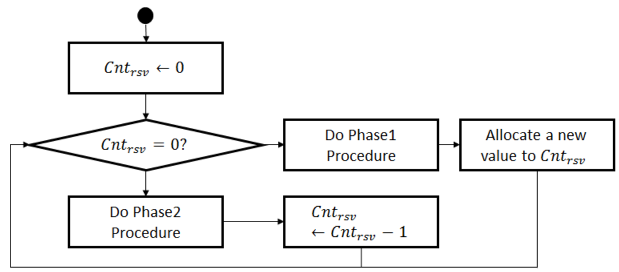

Fig. 3. Overall Flow of SNB

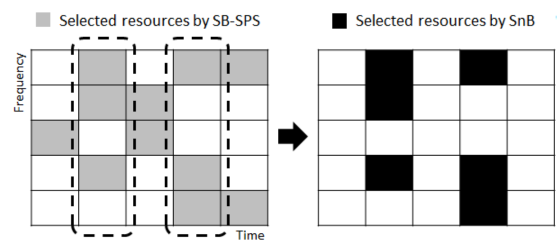

Fig. 4. (Left) Selected resources by SB-SPS; (Right) Final resource candidates selected after filtering out resources in non-least-used subframes

B. Phase 1 Procedure

The objectives of Phase 1 procedure are (1) selecting a contention-free resource and (2) minimizing the half-duplex problem based on balanced use of given time resource.

1) Selecting a contention-free resource: Because we consider the co-existence of SB-SPS, selecting a resource which has relatively smaller average RSRP than other resources is good strategy to select a contention-free resource. Hence, SNB recycles the resource candidate pool created by SB-SPS, and selects a resource from the pool.

2) Minimizing the half-duplex problem: If a vehicle selects a resource in a subframe which is not used by any other neighbor vehicles, the vehicle does not suffer from the half-duplex problem. In other words, when a vehicle select a resource in a subframe, the degree of suffers from the half-duplex problem depends on the number of occupied resource in the same subfrmae by neighbor vehicles. Hence, to minimize the half-duplex problem, a vehicle should select a subframe which would be the least-used subframe in the next round. Because the least-used subframes in the n^{th} round would be the least-used subframes again in the $(n+1)^{th}$ round with a high probability, SNB should select a resource in the least-used subframes in the n^{th} round.

Fortunately, the set of resources which would not be used in the next round is already collected in the resource candidate pool created by SB-SPS. Thus, SNB only needs to count the number of resources in the pool for each subframe. SNB then filters out the resources which are not in the least-used subframes from the pool. Examples of the exclusion are illustrated in Fig. 4. The grey resources in Fig. 4 (Left) are the resources in the resource candidate pool. Because subframes

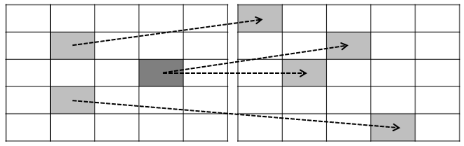

Fig. 5. (Left) Two vehicles use same subframe in column 2. Two vehicles use same resource in column 4. (Right) Resolving CMRFs via random selection.

1 (most left), 3, and 5 are not the least-used subframes, the resources in those subframes are filtered out by SnB from the pool, and the remainders in the pool become the final resource candidates for transmission as shown in Fig. 4 (Right). From the final resource candidates, SnB selects a resource randomly. To be consistent with SB-SPS, SnB also apply concept of SPS and use reservation count (Cnt_{rsv}). Let "r^{ph1}" denote the selected resource via Phase 1 in the remainder of this paper.

C. Phase 2 Procedure

Even though exploiting the concept of SPS is effective to avoid resource collisions by selecting a contention-free resource, SPS easily causes consecutive message losses due to repetitive same resource selection. Suppose, for instance, that two neighbor vehicles select resources in the same resource (or subframe) for their transmission in the n^{th} round. These vehicles will use the selected resources at least 4 more times for their future transmission because the minimum value of Cnt_{rsv} is 5. Thus, they cannot receive the reciprocal messages from each other for at least $5 \times t_{mb}$ milliseconds. Other vehicles cannot receive the one (or both) of the collided messages consecutively either. To avoid the problem of CMRFs, the objective of Phase 2 is to minimize the probability of consecutive message reception failures.

1) Shake — Resolving consecutive misses: To mitigate the problem of CMRFs due to either resource collision or half-duplex problem, conflicting resources should be separated in the next round. For example, if two vehicles use $r_{2,2}$ in the n^{th} round and their messages collide with each other, then they have to select different resources like $r_{1,1}$ and $r_{3,3}$ to avoid consecutive message losses.

In the context of fully-distributed resource allocation, the easiest and effective way of making this separation is selecting a resource randomly. For example, as shown in Fig. 5, if two vehicles use the same resource (or subframe) for their transmission in the n^{th} round, they cannot receive their messages. For transmission in the $(n+1)^{th}$ round, the vehicles randomly select resources to avoid consecutive message losses, and can thus receive the reciprocal messages from each other. Although the vehicles could select the same resource (or the same subframe) again as a result of the random selection, the probability of selecting the same resource (or the same subframe) is much lower than the probability of selecting different resources.

However, if a resource with the relatively low average RSRP is selected for the random shaking, the random movement could disrupt the selection procedures in Phase 1 and SB-SPS because the random selection raises the average RSRP of the selected resource. Suppose, for example, resource $r_{i,j}$ is not selected in the last t_{sense} (sensing window). Thus, the

Algorithm 1: Phase 2

Input : R: the set of given radio resources
r^{ph1}: the selected resource via Phase 1
DC: decoding map of resources
Output : r^{snb}: the selected resource for transmission

1 **if** $DC(r^{ph1})$ = *true* **then**
2   sort(R); // By average RSRP — descending
3     $ridx \leftarrow rand(0, R.size() \times 0.8)$;
4     $r^{snb} \leftarrow R[ridx]$;
5 **end**
6 **else**
7     $r^{snb} \leftarrow r^{ph1}$;
8 **end**
9 **return** r^{snb};

resource should be included in the resource candidate pool created by SB-SPS. However, if the resource $r_{i,j}$ is used for random selection, the average RSRP of the resource raises, so the resource could be excluded from the candidate pool.

To mitigate the disruption, SnB restricts the available resources for random selection by creating a random movement pool. The random movement pool is created according to the average RSRP of each resource. Initially, all the given resources are included in the random movement pool, and the given resources are sorted by their average RSRP as stated in Line 2 of Algorithm 1. Because the lowest 20% (N_r) of resources are chosen by the SB-SPS selection procedure, SnB selects the highest 80% of resources with respect to average RSRP as available resources for random selection. Thus, the lowest 20% of resources are excluded from the pool. From the random movement pool, SnB selects a resource randomly for the next round transmission. To be consistent with SB-SPS, SnB uses the same sensing window size to compute the average RSRP of each resource.

2) Back — Preserving the benefits of SPS: Random selection is effective, but makes it difficult to estimate/identify contention-free resources in Phase 1. Hence, the random selection could degrade the overall communication performance. To minimize the disruption, we intentionally make that the selected resource (r^{ph1}) in Phase 1 has higher average RSRP than the other not-selected resources. To achieve this, we reselect r^{ph1} if there is no decoded signal on r^{ph1}.

Suppose a vehicle selects r^{ph1} via Phase 1 in the n^{th} round and randomly selects a resource $r_{p,q}$ in the $(n+1)^{th}$ round. In this case, we expect r^{ph1} to be occupied by other vehicles in the $(n+1)^{th}$ round because the other SnB vehicles also select a resource randomly. However, the occupation of r^{ph1} in

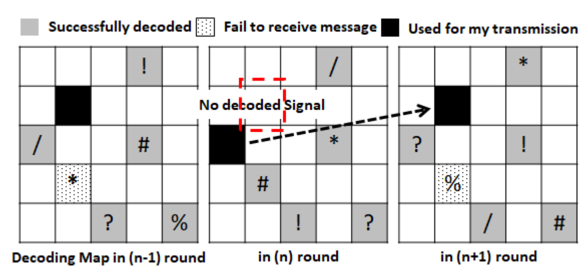

Fig. 6. Example of Shake and Back

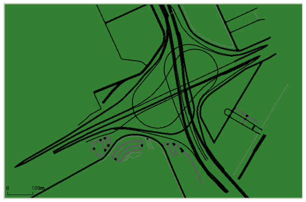

Fig. 7. Topology of highways in Detroit extracted from OSM

the $(n+1)^{th}$ round is not guaranteed, and thus r^{ph1} could be unoccupied in the $(n+1)^{th}$ round. In other words, the average RSRP of r^{ph1} could become smaller than other unselected resources, making it difficult to select contention-free resource in Phase 1. Hence, SNB intentionally re-selects the selected resource (r^{ph1}) for the next-round transmission if there is no successfully decoded signal on the selected resource as shown in Fig. 6. Then, the selected resource is used more than the unselected resource in the random resource pool as proved in the following Proposition 1. Hence, the selected resources are expected to have higher average RSRP than unselected resources.

Proposition 1. *The occupation probability of selected resources is higher than that of unselected resources in the random movement pool if the number of resources in the random movement pool is larger than that of neighbor vehicles, and neighbor vehicles have the same random movement pool.*

Proof: Let N_{rmp} be the total number of resources in the random movement pool, and N_v be the number of neighbor vehicles. Then, the occupation probability of a not-selected resource is bounded by $\frac{N_v}{N_{rmp}}$. To compute the occupation probability of a selected resource, we need to consider following two cases.

Case 1: A message is successfully decoded on the selected resource. The occupation probability of the resource in the next round is then bounded by $\frac{N_v-1}{N_{rmp}}$ because any vehicles can select the resource as a result of random selection.

Case 2: There is no decoded message on the selected resource: Then, the vehicle will choose r^{ph1}, and thus the occupation probability of the resource is 1.0.

Suppose the probability of Case 1 is x. Then, to hold this proposition, $\frac{xN_v-x}{N_{rmp}}+(1-x) \geq \frac{N_v}{N_{rmp}}$ must hold. We know that x is larger than or equal to 0.5. Thus, $\frac{(0.5)N_v-x}{N_{rmp}}+0.5 \geq \frac{N_v}{N_{rmp}}$ must hold. If $N_{rmp}-1 \geq N_v$, the inequality is always true, and the proposition follows.

VI. Evaluation

A. Simulation Setup

We evaluate SNB based on realistic simulations by using Network Simulator 3 (ns-3) [11]. For simulation, we have implemented the features for Mode 4 configuration defined in 3GPP Rel.14 on top of NIST LTE-D2D implementation [12]. To generate realistic simulation scenarios, we generated mobility traces on Detroit map using OpenStreetMap (OSM) Web Wizard provided by Simulation of Urban Mobility (SUMO) [8]. The extracted topology of Detroit is shown in Fig. 7.

Traffic Scenario: We generated 70 different traffic scenarios by controlling the SNB vehicle ratio (0%, 10%, 30%, 50%, 70%, 90% and 100%) and the average number of neighbor vehicles (η = 3.9, 6.6, 9.8, 11.8, 13.4, 16.5, 19.7, 21.3, 23.7 or 26.5) within 150m. Note that the generated mobility traces are imported into the ns-3 simulator using NS2MobilityHelper class.

Channel Model: We follow the V2V channel model used in simulations for the freeway case conducted by 3GPP [2]. Thus, we use the line-of-sight (LOS) WINNER+B1 pathloss model, and create the shadowing using log-normal distribution with 3dB standard deviation. For the case of less than 3m distance, the pathloss value for 3m separation is applied. Antenna is installed at the height of 1.5m.

CAM Broadcast: Every vehicle broadcasts 300-byte CAM periodically using 16-Quadrature Amplitude Modulation (16-QAM) with coding rate 0.5 as used in [2]. Thus, it requires 8 RB pairs for transmission, so there are 10 RB pairs per sub-channel (2 for SCI and 8 for CAM data). Every vehicle broadcasts CAM with 23dBm of transmission power in 5.9GHz ITS band. 20ms, 50ms and 100ms are used as the broadcast period, and it is configured that every vehicle use same period.

SB-SPS Configuration: The sensing window size (T_{sense}) is set to 1s. T_1 is set to 1 and T_2 is set to same as the message broadcast period. The resource re-selection probability (p_k) is set to 100%.

B. Results

1) Average MRR: We have measured the average MRR for different SNB vehicles ratios. As shown in Fig. 8 (left), even the small portion of SNB vehicles on the road helps increasing the average MRR by about 5%. The increase in the average MRR means that the SB-SPS and Phase 1 procedures select a contention-free resource well even with the disruptions from the random selection. Fig. 8 (center) and (right) show that high-density cases benefits more than low-density cases from the random selection in terms of the average MRR.

We have also measured the average MRR at different number of CMRFs for different SNB vehicles ratios. Fig. 9 shows that the average MRR at 0 miss decreases slightly as the SNB vehicle ratio increases. At the expense of this slight decrease of the average MRR at 0 miss, the average MRR at one or more consecutive misses increases. This increase mainly comes from the random selection to avoid CMRFs. Especially, the results show that the *Shake* is effective to increase the average MRR at 3 or more consecutive misses. For instance, the average MRR (with 20ms period) is 2.53× higher at 3 consecutive misses and 5.52× higher at 5 or more consecutive misses with 100% SNB vehicle ratio compared to 0% SNB vehicle ratio (100% SB-SPS vehicle ratio).

2) Update Delay: We also have measured the cumulative percentage as shown in Fig. 10 (center) and (right). With 0% SNB vehicles, messages can arrive within 100ms (200ms) with 95.3% (97.1%) probability in the $\eta = 26.5$ scenario. For the same scenario, with 100% SNB vehicles, messages can arrive within 100ms (200ms) with 97.6% (99.6%) probability. This means that SNB can make more robust communication than SB-SPS alone, thus realizing the various V2X services with more stringent requirements.

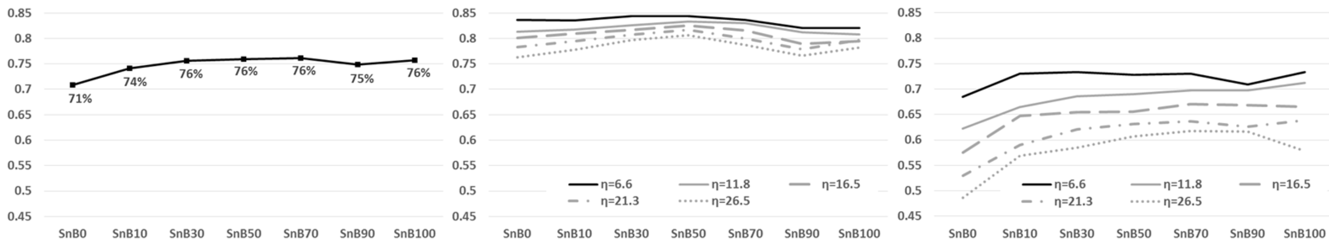

Fig. 8. (left) Average MRR for different SNB vehicles ratios. (center) Average MRR for different SNB vehicle ratios and different vehicle densities with 100ms broadcast period, and (right) with 20ms broadcast period

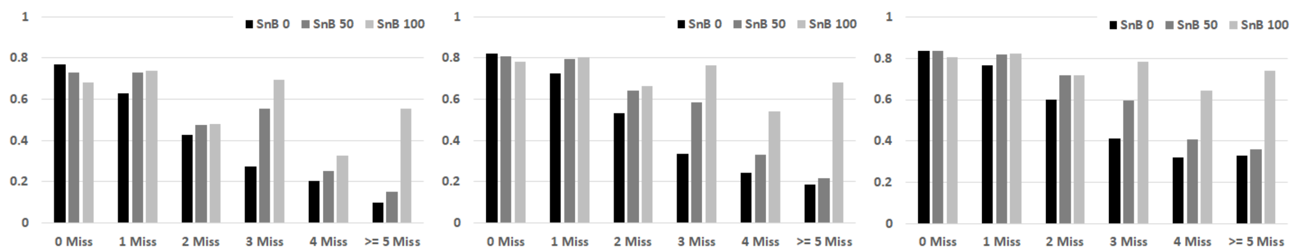

Fig. 9. Average MRR at different number of CMRFs (left) with 20ms period (center) 50ms period (right) 100ms period.

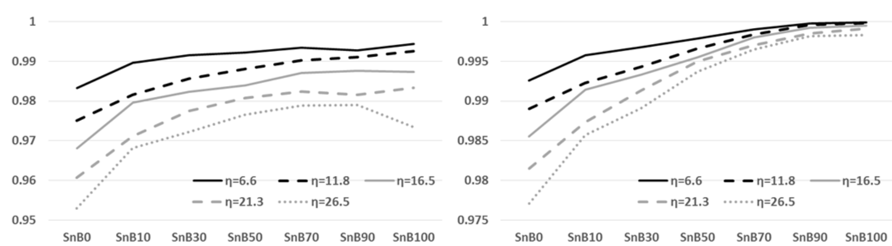

Fig. 10. (left) Cumulative percentage of update delay is $\leq$ 100ms for different densities (20ms broadcast); (right) Cumulative percentage of update delay is $\leq$ 200ms for different densities (20ms broadcast)

VII. Conclusion

In this paper, we discovered that SB-SPS easily causes CMRFs. To mitigate the problem of CMRFs, we propose a new fully-distributed resource-selection algorithm for Mode 4 configuration, called SNB. Simulation results show that SNB not only effectively addresses the problem of CMRFs, but also improves overall network performance. Since SNB complements SB-SPS effectively and hence enables their coexistence, we expect SNB to be deployed easily and soon in the field.

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