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RESEARCH ARTICLE

Geo-Based Resource Allocation for Joint Clustered V2I and V2V Communications in Cellular Networks

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ABSTRACT Cellular vehicle-to-everything (C-V2X) communications have gained traction as they can improve safe driving, efficiency, and convenience. However, mobility and the rising number of vehicles make the efficiency of resource allocation (RA) schemes more difficult. Different RA schemes have been proposed to share C-V2X resources effectively. Nevertheless, routing-aware RA has not attracted enough attention in the literature. This paper discusses various scenarios where routing-awareness can be employed in RA to improve the performance and proposes a routing-aware RA method that assumes a cluster-based routing for vehicle-to-infrastructure (V2I) communications and a geo-based RA for vehicle-to-vehicle (V2V) communications. V2I vehicles are grouped using the density-based spatial clustering of applications with noise (DBSCAN) algorithm and are connected to the cluster heads (CHs) using dedicated short-range communications (DSRC). In supposed scenario, CHs use cellular resource blocks (RBs) to forward vehicles' traffic toward the base station (BS). This paper proposes two heuristic algorithms that enable CHs to use some RBs already assigned to V2V communications for their V2I links without significantly affecting QoS requirements of V2V connections.The proposed algorithms take into account the formed V2I clusters and their loads, and are consequently routing-aware. Based on simulation results, the proposed algorithms improve spectrum efficiency by about 75% in average while the quality of V2V communications are maintained.

INDEX TERMS Routing awareness, geo-based resource allocation, cellular V2X, cluster-based routing.

I. INTRODUCTION

LTE technology has recently enabled communication between vehicles and evolved NodeBs (eNBs). In release 14, the 3GPP defines two ways to use available radio resources for vehicle-to-vehicle (V2V) communications, i.e., Mode 3 and Mode 4. Vehicles must be completely covered by an eNB (or multiple eNBs) that dynamically allocates resources to them for V2V communications in Mode 3 [1]. In Mode 4, vehicles are assumed to be in areas without cellular coverage, and distributed resource management is employed. Moreover, a semi-persistent transmission system based on sensing is provided to facilitate resource allocation (RA) in Mode 4 [1], [2], [3], [4], [5].

LTE and fifth-generation (5G) cellular networks have the potential to serve not only existing dedicated short-range communications (DSRC) use cases but also more complex and prospective use cases requiring low latency, high dependability, or high bandwidth. Undoubtedly, most vehicle-to-infrastructure (V2I) communications will be dominated by 5G technologies. By leveraging refurbished efficient air interfaces, a wide range of allocated bandwidth, innovative transceivers, multiple radio access technologies, and cutting-edge network softwarization principles, 5G intends to ensure ultra-low latency, ultra-high reliability, and high-data-rate V2I connectivity, with future driverless and safer vehicles made possible by V2V communications [6].

Many studies have been conducted in the literature for managing radio resources in vehicle-to-everything (V2X) communications that aim to increase total throughput,

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mitigate interference, and reduce latency [7], [8], [9], [10]. However, these RA methods are not appropriately aware of the routing decisions in the network layer of vehicular ad-hoc networks (VANETs). The authors of [5], [11], [12], and [13] opt to employ clustering for multiple V2X communications purposes. In [11], the resources are partitioned into orthogonal groups to reduce resource collision, and then the cluster head (CH) selects resources by sensing for available resources. However, the number of resources in those groups could be determined based on the clusters load. In [12], according to the sensing results, the CH decides for its cluster members (CMs) to minimize interference. This means that construction of clusters is made based on resource availability while the availability of resources in different cells/areas could be adjusted based on the load of clusters there. The references [5], [13], [14] have an appetite in the assignment of resources in V2X communications and offer cluster-based resource allocation for V2V communications, a cluster-based resource selection scheme for 5G V2X, and a two-level cluster-based routing strategy for 5G V2X communications. However, these works have not addressed the concept of routing-awareness in resource allocation.

Geo-based RA is another RA technique utilized in cellular-V2V (C-V2V) networks in which the entire vehicular area is divided into sub-areas (SAs) of equal size. Using a predefined mapping, frequency is reused by vehicles located in different SAs with sufficient distance to preserve channel quality [15]. The mapping specifies which RBs (sub-resource pool) are assigned to each SA. This map is disseminated to all vehicles in the area. Thus, each vehicle is aware of its location and so its current SA. Moreover, energy-sensing is defined by each SA's vehicles to select suitable free resources from the assigned sub-resource pool [16], [17]. These methods are not also aware of routing decisions in network layer while multi-hop packet forwarding is a possible scenario in V2V communications that the geo-based RA may consider it to make better resource partitioning and resource assignment to SAs. Moreover, the resources considered for V2V communications may be useless in some SAs while routing-ware mapping of RBs to SAs could allow some RBs to be released for V2I communications.

Based on above discussions, routing-aware RA has not been addressed appropriately in the literature on C-V2X communications. It is while routing awareness is an important issue in RA for both V2I and V2V scenarios and improves RA performance. This article discusses the importance of routing-aware RA in various scenarios of C-V2X and proposes a routing-aware RA for a specific heterogeneous VANET scenario which consists of cellular V2V communications and cluster-based V2I communications. In this scenario, we assume that vehicles with V2I traffic use cluster-based routing. These vehicles are clustered using a clustering algorithm such as density-based spatial clustering of applications with noise (DBSCAN). Consequently, CH receives traffic from associated CMs via DSRC. CH then uses cellular resources to forward the cluster's traffic over a V2I link. We propose two routing-aware geo-based RA algorithms that release some RBs already dedicated for V2V communications, for use by V2I cluster heads to route their traffic to the eNB, without violating the quality of service (QoS) requirements of V2V traffic. The proposed algorithms consider the load of constructed V2I clusters in their RA decisions (in addition to V2V traffic), and are consequently routing-aware. Briefly, the contributions of the paper are as below:

- Discussing routing-aware resource allocation in vehicular networks and presenting various scenarios that routing-awareness may improve the performance of the RA.
- As one of the possible routing-aware resource allocation scenarios, proposing an RA scheme that considers the information on V2I routing clusters to reclaim appropriate V2V resources for use in V2I communications.
- Proposing two routing-aware heuristic algorithms that release those V2V resources for use in clustered V2I communications by re-arranging the result of a geo-based V2V RA algorithm.

This paper is structured as follows: related work is reviewed in Section II. The idea of routing-aware resource allocation in C-V2X and some possible scenarios are discussed in Section III. The explanation of the system model and the proposed solution are provided in Section IV. The simulation results are presented in Section V, followed by a discussion of the conclusion and an examination of prospective future work in Section VI.

II. RELATED WORK

Recent interest in V2X, a technology that enables intelligent transportation systems, has focused on improving traffic flow, road safety, and entertainment needs. Diverse techniques are utilized for V2X radio resource allocation. Recent studies, such as those cited in [1], [2], [3], [4], [5], [6], [7], [8], [9], [17], [18], [19], [20], [21], [22], and [23], seek to provide a comprehensive picture of radio resource allocation in V2X communications.

The resource-sharing issue in VANETs (with V2V and V2I communication) is the primary focus of [17] and [18], which presents multiple interference graph-based resource-sharing techniques to address this issue. The two systems are the interference-aware graph-based resource-sharing method and the interference-categorized graph-based resource-sharing scheme. These two proposed approaches aim to reduce the high communication cost while achieving suboptimal performance and a higher network sum rate than the conventional orthogonal communication mode. Reference [19] develops a three-dimensional RA strategy for V2V communications. The plan uses three-dimensional graphs and hyper-graph coloring to assign RBs for V2V communications. It intends to increase the capacity of V2I lines while ensuring minimal QoS standards for cellular user equipment (UEs). The interferences and UEs are represented as the graph's edges and vertices, respectively. The authors suggest a centralized resource allocation plan for non-orthogonal multiple access (NOMA) integrating device-to-device (D2D) and 5G vehicular networks in [20]. The system capacity is intended to be enhanced and maximized in this way. To accomplish this, the base station (BS) assigns sub-channels to each vehicle group during each transmission period; each group then decides allocation and power control. The approach suggested in reference [21] is called a hyper fraction. It gives resources to each area after dividing the roads into distinct regions. Every vehicle in the associated zone utilizes the designated channels for this zone. Based on hyper-fraction, this technique allows the system to minimize communication delay. All above methods do not attend to network layer routing decisions and their effects on the resource allocation efficiency.

The researchers presented a novel resource allocation system in cellular V2X network Mode 3 to maximize vehicular connections and CUE QoS in reference [22]. First, the authors describe the resource allocation optimization issue in the C-V2X network Mode 3, considering the high mobility of VUEs and the lack of global channel state information (CSI) of mobile connections at the BS. Next, the BS should provide power and sub-carriers to cell phone and vehicle users to reduce unauthorized vehicular connections. The authors of [23] propose deep learning to improve the efficiency of V2I and V2V connections and resource allocation in V2X communications. The primary objective of the proposed strategy is to improve the resource allocation to adapt rapidly to a changing environment. Nonetheless, convergence speed remains a challenge. The authors of [24] propose a novel strategy known as "the combined share and dedicated allocation of resources." The proposed solution is based on graph theory and attempts to maximize the capacities of D2D UEs while ensuring that the shared mode power restriction of D2D UEs has no impact on the performance of cellular UEs. In [25], researchers introduced a hybrid automated scheduling and RA scheme for D2D-based V2X communications. These works do not attend to the network layer routing decisions in possible multi-hop communication scenarios.

To satisfy the reliability and latency requirements, the authors of [12] proposed a solution which involves a combination of resource allocation and traffic sharing among different types of users, including CUEs, non-safety VUEs, and safety VUEs. Their suggested method aims to optimize the sum rate of CUEs while taking into account delay constraints for safety VUEs and CUEs, as well as SINR for all users. RBs allocated to CUEs can be reused by non-safety and safety VUEs, with no more than one RB shared between three distinct users from different classes, while considering the needs of each class. The approach presented in references [5] addresses the challenge related to non-orthogonality exhibited by VUE by sharing VUEs and RBs successively. The more interference a VUE may generate, the less likely it is that it will share the same RB with another VUE in an ideal allocation. The authors use this concept to transform clustering into graph partitioning. However, the suggested approach for graph segmentation is NP-hard. References [13] and [14] focus on V2V communications and aim to minimize resource collisions using a cluster-based resource selection. To prevent resource collisions, resources are partitioned into orthogonal sets and each cluster head selects a resource set based on interference. In more detail, the cluster head chooses resource set with the least interference and plans the resources for cluster members to minimize resource collisions. All above methods do not explicitly consider the clusters' loads into their decisions and only assign the resources in a cluster-based manner.

In this paper, we firstly discuss the importance of routing-awareness in V2X RA schemes. Then, in contrast to the studies mentioned above, we propose two algorithms that are routing-aware and improve a geo-based V2V RA scheme by allowing it to use some RBs for clustered V2I communications without violating QoS requirements of V2V communications. These algorithms are routing-aware as they consider the load of clusters (constructed via a cluster-based routing algorithm for V2I communications) in their RA decision. Proposed algorithms attempt to use some V2V RBs for some V2I clusters to improve the total throughput while meeting the requirement of V2V links.

III. ROUTING-AWARE RESOURCE ALLOCATION IN VEHICULAR NETWORKS

Routing plays a crucial role in the context of vehicular networks. Efficient routing schemes help to ensure that data is transmitted reliably and efficiently between connected vehicles and infrastructure components. However, proper resource allocation is essential in routing performance, since a large number of vehicles leads to a lack of radio resources in C-V2X. From the other side, routing algorithms have considerable effect on the performance of resource allocation scheme in C-V2X. Routing-aware resource allocation is a powerful approach that can significantly improve the performance of RA by considering the paths or clusters that are made by routing algorithm. Routing-aware RA can improve spectrum efficiency and increase network capacity.

Therefore, routing can be relied upon to be almost indispensable when making crucial and optimal decisions for management of available resources. However, previous works have not adequately attended to this approach and varying scenarios that routing awareness could be applied to improve the efficiency, as discussed in previous sections. Various scenarios are possible where routing-awareness could improve the performance. Routing protocols are used in V2V communications to form multi-hop links between source and destination vehicles. This type of communication is used in C-V2X environment to locally reuse radio resources in a multi-hop manner for both unicast [26] and multicast/geocast [27] communications. Routing-awareness is essential in those scenarios to better manage the cellular radio resources that are dedicated to V2V communications. Based on the fact that which vehicles are in which routing paths, the cellular resources can be more appropriately allocated to V2V pairs

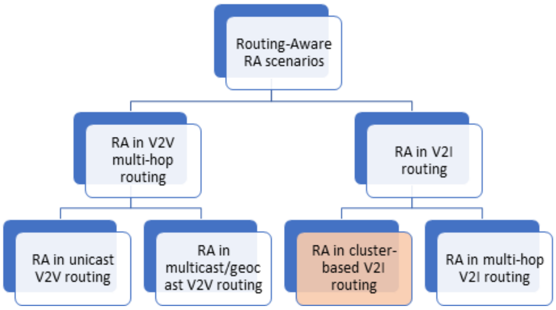

FIGURE 1. **Some possible scenarios for routing-aware resource management in C-V2X.**

along the paths regarding their local interference on other neighboring V2V pairs.

Furthermore, routing is used in V2I scenarios for downlink/uplink communications from/to the BS for various applications such as video streaming and entertainment. V2I routing can be performed in cluster-based or multi-hop manner. In cluster-based method, traffic is routed to/from the BS through a cluster head [28] while in multi-hop manner, the traffic is relayed by multiple vehicles to/from the BS [29]. In these scenarios, routing-awareness is yet essential to more efficiently allocate V2I resources (to clusters or relaying vehicles) or even release some unused resources dedicated for V2V communications as is the case of the method presented in this paper. Figure 1 shows the scenarios where routing-awareness is recommended for radio resource management.

In the following section, we focus on the routing-aware RA in cluster-based V2I routing scenario (as marked in Figure 1) and take the advantages of being aware of the clusters in management of V2V resources for possible use by cluster heads. The routing-aware RA method proposed in this paper, takes loads of constructed V2I clusters into account to modify a geo-based RA to release some resources already dedicated for V2V communications and assign them to loaded clusters. Other scenarios of Figure 1 are candidates for future work.

IV. PROPOSED METHOD

This section describes our proposed routing-aware RA algorithms for a typical VANET scenario with V2I and safety V2V communications. First, the system model is presented in subsection A, followed by the proposed algorithms in subsection B. An illustrative example is subsequently provided in subsection C.

A. SYSTEM MODEL

We assume that vehicles requiring V2I communications exploit a cluster-based routing (e.g., DBSCAN clustering algorithm) and their traffic is not mission-critical. DSRC is used for intra-cluster communications, connecting vehicles within a cluster to the CH. Then, CHs send packets of their CMs to the BS using cellular resources. Figure 2 illustrates clusters (yellow polygons) served by a BS via cellular V2I communication. Notably, the V2I vehicles not clustered connect directly to the BS via cellular resources and are assumed to be CHs without a CM. The CHs are associated with the BS with the highest signal strength. For V2V communications, geo-based resource allocation is used, which divides the area into a number of SAs (black circles with white numbers) so that vehicles in each SA utilize the cellular radio resources assigned to that area.

Each BS has a resource pool consisting of a number of RBs, denoted by R, of which $\alpha\%$ are reserved for V2I links (R_{V2I}), and the remaining RBs are dedicated to V2V links (R_{V2V}). V2V communications have a higher priority than V2I communications in our model because those are assumed to be used for safety applications. Therefore, the majority of RBs are dedicated to V2V traffic. V2I resources are assigned to CHs using a fair scheduling algorithm [30]. In geo-based V2V RA, the R_{V2V} resource blocks are divided into n sub-resource pools (SRs), each of which is reused in multiple SAs. An SR is reused in SAs that are sufficiently separated from one another. We assume that SRs are assigned to SAs, according to [15] and [16]. In [15], the vehicular area is partitioned into $i \times j$ geographic regions which are represented as a grid and numbered independently of which BS covers them. A typical scenario with 32 regions and 8 sub-resource pools is shown in Figure 2. (SRs are denoted by B, D, F, H, I, J, K, and L). It should be noted that each SR represents a percentage of the overall resource pool, and that there are several RBs in each SR. In addition, we assume that the QoS requirement of each V2V link can be met with a single RB. In [15], sub-resources are allocated to SRs dynamically so that the number of RBs in a jam SA be more than sparse SAs. All of the SAs are split into N groups and each group comprises M SAs, where M is the number of areas divided by the number of groups. Then the SAs are grouped such that each group has almost the same number of jam areas and its SAs be close to one another. Then, any N best SAs where each one belongs to a different group are clustered to reuse the same SR. Those areas are the ones that are not only far away from each other adequately (regarding a distance metric), but also have the almost close density of vehicles (regarding a density metric). Density metric indicates how similar these clustered SAs are in terms of the number of vehicles inside them. A weighted combination of these two metrics is used as the final metric to cluster the SAs. Then the sizes of SRs are adjusted based on the densest SA in a cluster of SAs. Figure 2 depicts the assignment of SRs to SAs for V2V communications (colored circles with particular letter for each SR). For example, in Figure 2, the SAs 1, 5, 18, and 22 are clustered to reuse the same SR (SR_B). It is noteworthy that V2I vehicles' clustering is independent of the above mentioned V2V area clustering and resource assignment.

For V2I communications, RBs could not be reused by the vehicles in a BS; thus, limited resources will increase the access delay. Hence, we propose to exploit useless V2V resources for V2I. Each BS clusters its serving V2I vehicles independently of V2V SAs, using DBSCAN. Then, each

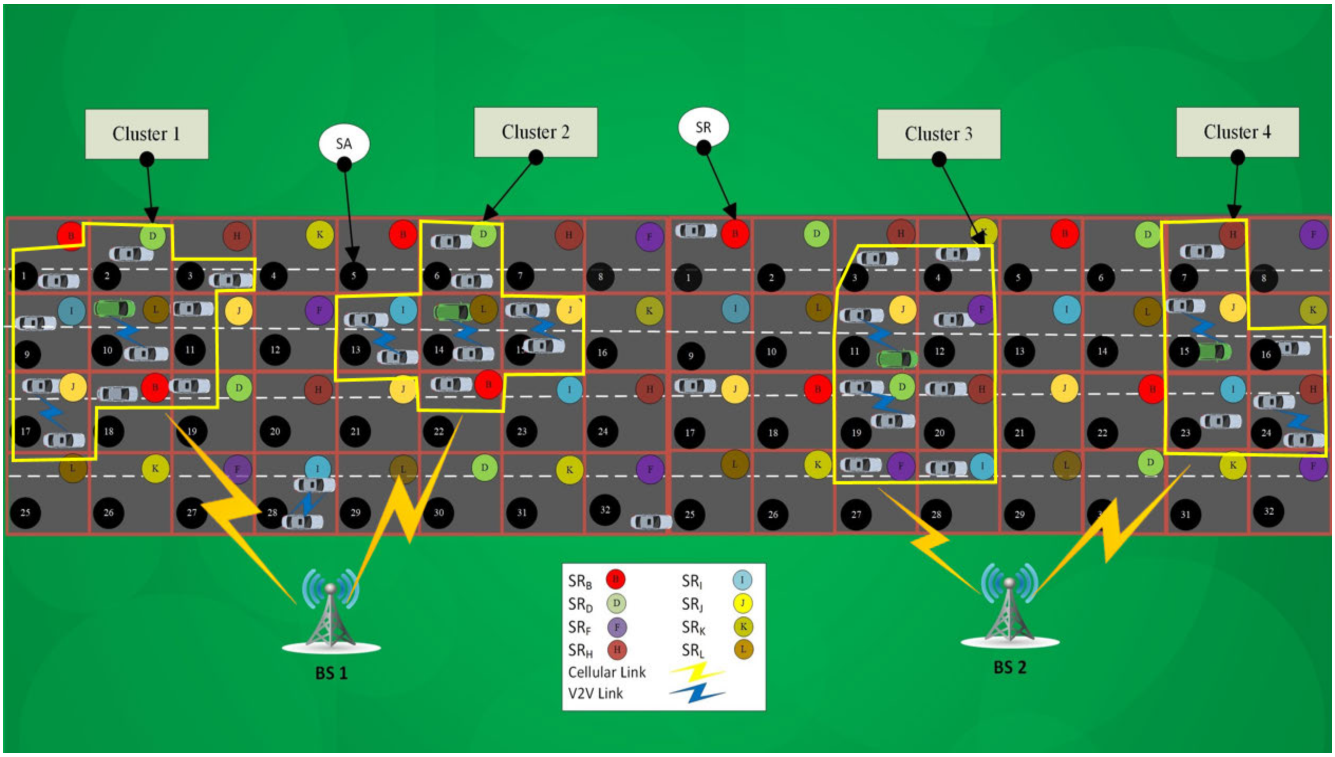

FIGURE 2. **Geo-based V2V and clustered V2I communications; the area is partitioned to equal-size sub-areas where black circles represent SA number (from 1 to 32), V2V SRs are denoted by colored circles such as *B* (for SR_B), *D* (for SR_D), *F* (for SR_F), *H* (for SR_H), *I* (for SR_I), *J* (for SR_J), *K* (for SR_K), *L* (for SR_L), and V2I clusters are displayed by yellow polygons (Cluster1, Cluster2, Cluster3, Cluster4).**

CH is allowed to use the V2V radio resources that aren' used at any SA under the coverage of the BS, regarding the algorithms proposed in next subsection. Table (1) shows the paper's notations and descriptions. The proposed method employs a routing-aware re-arrangement algorithm to temporarily utilize free V2V SRs/RBs to improve the quality of V2I communications routed through CHs. The method will be discussed in the subsequent section.

DBSCAN algorithm is used for clustering because, in contrast to previous ones such as Mean-Shift algorithm [31], it does not require to predefine the number of clusters, and it constructs clusters with unusual shapes in low time complexity. The DBSCAN-based clustering method groups neighboring vehicles in a cluster, and get their connections through CH. Standalone vehicles also communicate directly through a BS using V2I links. CH plays the role of relay node for the DSRC CMs and redirects their traffic to a BS via a cellular connection. In the algorithm, vehicles are evaluated concerning their surrounding vehicles to form clusters. The vehicles with sufficiently adjacent neighbors, i.e., N_{min} neighboring vehicles within the radius ϵ, are considered as core vehicles that are allowed to make clusters [32]. The DBSCAN-based vehicle clustering is displayed in Algorithm 1. Equation (1), as shown at the bottom of the page, shows various types of vehicles defined in this algorithm. There, $|N_\epsilon(x)|$ shows how many vehicles are around vehicle x within a maximum distance of ϵ. In line 14, equation (1) is used to determine whether node x is a core node (CH) or not regarding the number of its surrounding vehicles whereas in line 8, equation (1) is used to determine vehicle x as a noise vehicle which will not belong to any cluster. Finally, equation (1) is used in line 12 to determine a vehicle as a border vehicle, which means that the vehicle is a member of another cluster. The time complexity of this algorithm is $O(n^2)$ in the worst case where n is a number of vehicles.

B. RESOURCE RE-ARRANGEMENT ALGORITHM

As stated before, this paper takes loads of constructed V2I clusters (created by DBSCAN algorithm) into account to modify a geo-based RA to release some resources already

$$x = \begin{cases} \mathit{core\ vehicle}(CH) & \text{if } |N_\epsilon(x)| \geq N_{min} \text{ and } \nexists\, y \in \{N_\epsilon(x)\} \mid \ y \in \{CH\} \\ \mathit{border\ vehicle}(CM) & \text{if } |N_\epsilon(x)| < N_{min} \text{ and } \exists\, y \in \{N_\epsilon(x)\} \mid \ y \in \{CH\} \\ \mathit{noise\ vehicle} & \text{if } |N_\epsilon(x)| < N_{min} \text{ and } \nexists\, y \in \{N_\epsilon(x)\} \mid \ y \in \{CH\} \end{cases} \tag{1}$$

TABLE 1. Notations and their descriptions.

Notation	Description
R	Set of RBs
SR	Set of sub-resource pools
R_{V2I}	Set of RBs assigned to V2I traffic (through CHs)
R_{V2V}	Set of RBs assigned to V2V communications
C	Set of clusters
CH	Set of cluster heads
SA	Set of sub-areas
n	Number of sub-resource pools (|SR|)
k	Number of sub-areas (|SA|)
γ^i	The queue load of the i^{th} CH
Q^i	The queue of the i^{th} CH
S^i	Queue size of the i^{th} CH
SR_{ll}	Set of SRs whose load is lower than θ_{SA}
RB^i_{free}	free RBs of the i^{th} SR
RB^i_{need}	RBs needed by the i^{th} CH
SA^n_{max}	Maximum-load SA among the SAs which use n^th SR
$load(SR^n)$	Load of SR regarding the SA with a maximum load that uses this SR
$load^i_{CH}$	Load of the i^{th} CH
$load(SA_i)$	Load of the i^{th} SA
$size(SR^h)$	Number of usable RBs in SR^h
ϵ	Distance threshold of DBSCAN algorithm
N_{min}	Minimum number of vehicles required within ϵ coverage of the cluster head

Algorithm 1 DBSCAN-Based vehicles' Clustering

```
Input: $N_{min}$, $\epsilon$, $\{Vehicles\}$
Output: $Clusters$
Begin
$D_{unprocessed} \leftarrow \{Vehicles\}$
$no\_of\_clusters = 0$
while ($D_{unprocessed} \neq \emptyset$) do
    for each vehicle x $\in D_{unprocessed}$ do
        if $|\ N_\epsilon(x)\ | < N_{min}$ and $\nexists\ y \in N_\epsilon(x)$ that y is a core vehicle then
            Mark x as noise vehicle
            $no\_of\_noise\_vehicles$ ++
            $D_{unprocessed} \leftarrow D_{unprocessed} - \{x\}$
        else if $|\ N_\epsilon(x)\ | < N_{min}$ and $\exists\ y \in N_\epsilon(x)$ that y is a core vehicle then
            Mark x as border vehicle
        else if $|\ N_\epsilon(x)\ | \geq N_{min}$ and $\nexists\ y \in N_\epsilon(x)$ that y is a core vehicle then
            Mark x as core vehicle
            $no\_of\_clusters$ + +
            $D_{DR(x)} \leftarrow$ all distance_reachable vehicles from x that are in D_unprocessed
            $Clusters_{no\_of\_clusters} \leftarrow \{x\} + D_{DR(x)}$
            $D_{unprocessed} \leftarrow D_{unprocessed} - Clusters_{no\_of\_clusters}$
        endif
    endfor
endwhile
end
```

dedicated for V2V communications and assign them to loaded clusters. Although a fixed portion of radio resources are already allocated to V2I communications by the BS (as stated in system model), V2I clusters are more supported by the vacant V2V resources in our method. Dynamic re-assignment of unused V2V resources for temporary use by CHs is proposed to improve spectrum utilization and the quality of V2I applications. Occasionally, a V2V sub-resource pool may be unused, or some of its RBs may be unused across all associated SAs. In our proposed method, such resources are lent to CHs that require additional RBs regarding the knowledge about their load.

Each V2I link (CH^i) is assumed to have a queue for its traffic to the cellular core. Assuming that CH^i's queue (Q^i) has a capacity of S^i, it is loaded if Q^i_{load} is greater than $\gamma\%$ of S^i (where $\gamma < 1$) and thus requires additional resources. Such a CH can be supported by 1) an SR or 2) several RBs of R_{V2V} if and only if the SR in question belongs to low-load SAs or the RBs in question are unused. Based on these two directions, two greedy algorithms are proposed. As shown in first algorithm (Algorithm 2), the first greedy approach temporarily returns some unused/under-utilized V2V SRs to V2I links, provided that V2V communications are not significantly impacted. The second algorithm (Algorithm 3) temporarily returns unused RBs to V2I clusters without significantly impacting V2V communications.

In Algorithm 2, first, the SRs are ordered by their load, i.e., based on the number of vehicles in the busiest area among the areas which use that SR (line 3). Thereafter, CHs are sorted in descending order by Q^i_{load} and CHs with a queue load exceeding $\gamma\%$ of queue capacity are remained in CH vector as candidates for exploiting the low-load SRs (line 4). Then, we chose SRs from the lowest load up to the one with the threshold load, θ_{SA} (lines 5-6). The lowest load SR is the SR with the greatest number of unused RBs to be handed for V2I links, which is always SR^1 in our sorted list (as we remove investigated SRs and resort the list in lines 12-13). A selected SR is considered as a candidate to be assigned to a CH if the free RBs of an alternative SR can support the V2V links in SAs that used that candidate SR. This is checked in the loop presented in lines 8-16 by only considering the SA with maximum load that use the candidate SR (SA^1_{max}). To support the V2V links whose SR is borrowed, this loop begins with the SR with the highest load (the SR that is used in SA_{max}) since it has the fewest unused RBs. When an alternative SR found that could support that SA (and consequently other SAs with lower load that should reuse candidate SR) too, the loop

Algorithm 2 Sub-Resource Pool Lending for Clustered V2I Communications in a Geo-Based V2V Resource Allocation Scheme

```
1:  Input: $SA$, $SR$, $RB_{need}$, $\gamma$
2:  Begin
3:  $ascending\_sort_{load}(SR)$
4:  $descending\_sort^{\gamma}_{load}(CH)$
5:  while true do
6:      if $load(SR^1) \leq \theta_{SA}$ then
7:          $SA^1_{max}$ = maximum_load SA that uses $SR^1$
8:          for $h = |SR|$ to 1 do
9:              if $size(SR^h) - load(SR^h) > load(SA^1_{max})$ then
10:                 $size(SR^h) = size(SR^h) - load(SA^1_{max})$
11:                 $SR_{ll} = SR_{ll} \cup \{SR^1\}$
12:                 $SR = SR - SR^1$
13:                 $ascending\_sort_{load}(SR)$
14:                 break
15:             endif
16:         endfor
17:     else break
18: endwhile
19: for $m = 1$ to $|CH|$ do
20:     if $RB^m_{need} \leq size(SR^m_{ll})$ then
21:         $R^m_{V2I} = R^m_{V2I} + \{SR^m_{ll}\}$
22:     endif
23: endfor
24: end
```

Algorithm 3 RB Lending for Clustered V2I Communications in Geo-Based V2V Resource Allocation Scheme

```
1:  Input: $SR$, $RB_{free}$, $RB_{need}$, $\gamma$
2:  Begin
3:  $ascending\_sort_{load}(SR)$
4:  $descending\_sort^{\gamma}_{load}(CH)$
5:  while $|SR| > 0$ do
6:      if $load(SR^1) \leq \theta_{SA}$ then
7:          $SR_{ll} = SR_{ll} \cup \{RB^1_{free}\}$
8:          $SR = SR - SR^1$
9:      endif
10: endwhile
11: for $m = 1$ to $|CH|$ do
12:     if $RB^m_{need} \leq |SR_{ll}|$ then
13:         $R^m_{V2I} = R^m_{V2I} + RB^m_{need}$
14:         $SR_{ll} = SR_{ll} - RB^m_{need}$
15:     endif
16: endfor
17: end
```

is broken (line 14). Those candidate SRs are maintained in SR_{ll} to be assigned to V2I CHs. Since demanding CHs and those candidate SRs are sorted, the first CH will receive the SR with the lowest load in our greedy algorithm provided that its needs (RB^1_{need}) are supported by SR^1_{ll}, followed by the next CH, and so on (lines 19-23). The time complexity of this algorithm is O(n^3lg$n$) in the worst case.

Algorithm 3 demonstrates our second greedy approach for lending resources of low-load SAs to high-demand CHs in a finer granularity. First, similar to Algorithm 2, CHs and SRs are sorted (lines 3-4). In this algorithm, a low-load SR (regarding a threshold, θ_{SA}) is not completely loaned for demanding V2I links, but its extra RBs (RB^1_{free}) are borrowed for those V2I links, as added to SR_{ll} in line 7. In contrast to Algorithm 2, we do not need to compensate the SAs associated with candidate SR using the resources from other SRs, since only unused RBs of each candidate SR are assigned to demanding CHs. Therefore, the unused RBs collected in SR_{ll} are assigned to demanding CHs according to their order (lines 11-16). The time complexity of the algorithm is O($n$lg$n$ + $p$lg$p$). Although this algorithm seems faster than Algorithm 2 in worst case, but in most cases, Algorithm 2 is not so slow compared to Algorithm 3. Moreover, using Algorithm 2, we do not violate the SR-based rule of V2V resource partitioning and when the V2V resource allocation of [15] modifies the size and the RBs of SRs (as is decided based on the density metric), the V2I clusters are not affected and can yet use the previously assigned SRs.

C. ILLUSTRATIVE EXAMPLE

This section provides an illustrative example of how the system model operates. In Figure 2, we assumed a V2V area which is divided into 32 equal-size SAs, i.e., SAs = $\{SA_1, SA_2, \ldots, SA_{32}\}$ which are numbered by black circles. We assume $p = 4$ V2I clusters with the R_{V2I} distributed among these four CHs (each with eight RBs). The RBs considered for V2V communication (R_{V2V}) are divided into eight SRs, i.e., SR = $\{SR_B, SR_D, SR_F, SR_H, SRI, SRJ, SR_K, SR_L\}$. Consider that each CH has a queue with size $S = 10$, γ is equal to 80%, and each vehicles sends one packet that needs one RB, As each vehicle needs one RB for its current packet to send, there is a direct relation between the number of vehicles in an area and its load in our example. CH_1 and CH_2which are heads of cluster 1 and cluster 2, and are associated to BS_1, have more than eight vehicles in their clusters and consequently lack adequate resources to forward the traffic received from all their CMs, on time. As a result, CH_1 and CH_2 are supposed to be loaded. Based on our proposed algorithms, the CH_1 will be served first because it has the highest load.

So, Algorithm 2 sorts the SRs related to BS_1 as $\{SR_k, SR_H, SR_F, SR_D, SR_I, SR_B, SR_J, SR_L\}$ and candidates (SR_K and SR_H) are chosen based on $\theta_{SA} = 2$. Thus, SR_K is lent to CH_1, i.e., $R^{(CH_1)}_{V2I} = R^{(CH_1)}_{V2I} + SR_K$. Next, SR_H is selected for CH_2, which is the next loaded CH, i.e., $R^{(CH_2)}_{V2I} = R^{(CH_2)}_{V2I} + SR_H$. Other SRs with adequate free resources will compensate the SAs of the loaned SRs, beginning with the SR with the fewest available RBs. Hence, SR_L is also used in SAs which already used SR_K, and SR_J is also used in SAs which already used

SR_H. The same procedure is executed for CH_3 (associated to BS_2) which is loaded by 10 vehicles, and the lowest load SR (SR_B) will be loaned to it for V2I communications, which later can be compensated by SR_H (since SR_H has fewest available resources and compensates shortcomings). When a CH requires fewer resources than a full SR and Algorithm 3 is used instead of Algorithm 2, fewer resources are wasted because required RBs are borrowed from a low-load SR rather than the entire SR. Therefore, the remaining RBs are assigned to the subsequent CH, allowing more V2I requests to be supported.

V. SIMULATION RESULTS

The proposed method is stimulated and its performance is evaluated using MATLAB. The simulated vehicular traffic conditions corresponded to the next-generation simulation (NGSIM) program's datasets, which include a variety of actual highway settings [33]. We choose various stretches of I-80, US101, Peachtree, and Lanker Shim. These sections of the dataset have been scaled to 1000m and separated into equal-sized subareas for five lanes road. Three areas of the dataset with different densities and distributions of cars were considered. The simulation results are average of 200 runs with various random seeds in each scenario which runs are different in the number of vehicles randomly selected from the dataset with respect to the threshold, x, as indicated in Table (2). The first scenario is a low-density, sparsely populated area. The second scenario is a V2I/V2V area that leads to SAs with extremely similar density (almost like a uniform distribution). The third scenario describes an area with a high concentration of cars whose distribution comprises multiple clusters. A number of vehicles in each scenario are considered for V2I traffic and the remaining are V2V pairs (almost equal) as shown in Table (2). A BS is considered to have a distinct collection of RBs, which are divided into sub-resource pools. Simulations were conducted to evaluate the performance of the proposed method in the aforementioned scenarios assuming a various number of available RBs (i.e., 100∼200). The simulation's parameters are shown in Table (2).

As the number of vehicles in each scenario is different from the others, for each scenario, we have chosen a distinct α value in such a way that the resources allocated for its V2I communications be in short supply. Choosing the same α value for all scenarios results in unfair comparisons, since in this case, some of the scenarios may not need more resources to be borrowed from V2V part. Therefore, the value of α is determined based on some experiments. We consider low values of α for two reasons: 1) satisfying the V2V connections with mission critical traffic, and 2) showing that how significantly our proposed method supports V2I traffic by vacant V2V radio resources when the pre-assigned V2I resources are not adequate. The α value must be balanced between preventing significant block rate in V2I communications on one side, and avoiding considerable V2I resource wastage. Figure 3 shows R_{V2I} wastage versus different values of α at each scenario. As seen, we have resource wastages in V2I communications when we dedicate more than 30% of resources for V2I communications (as R_{V2I}) especially for scattered scenario and then uniform scenario. So, we have selected 0.1, 0.15, and 0.2 for α in scattered, uniform, and multi-cluster scenarios, respectively, as shown in Table (2).

TABLE 2. Simulation parameters.

Parameters	Value
Number of vehicles (x)	“In a scenario with scattered vehicles: <100 (V2V = 54.5% of x, V2I = 45.5% of x)". “In a scenario with uniform distribution of vehicles: 100 to 200 (V2V = 61% of x,V2I = 39% of x)". “In a scenario with multi-cluster vehicles: >200 (V2V = 61% of x,V2I = 39% of x)".
SR	$\{SR_B,\ SR_D,\ SR_F,\ SR_H,\ SR_I,\ SR_J,\ SR_K, SR_L\}$
Number of SAs	32
α	"In a scenario with scattered vehicles: 0.1". "In a scenario with uniform scenario vehicles: 0.15". "In a multi-cluster scenario: 0.2".
θ_{SA}	5
Number of RBs	$100 \sim 200$
Road length in each scenario	1000 m
N_{min}	6 vehicles
ϵ	50 m

The proposed method is compared to the strategy described in [15]. The method in [15] exploits geo-based resource allocation for V2V communication and determines which SAs are assigned to which SR. To the best of our knowledge, this is the nearest work to our work and its V2V resource allocation is the one used by our proposed method. Hence, we can fairly evaluate the performance of our proposed algorithms if we assess that how effectively our algorithms use the vacant V2V resources of this method for V2I links. In addition to V2V communications, the baseline method is also assumed to manage V2I communications similar to our approach (considering the same number of RBs for V2I communications). The evaluation metrics used in our comparisons and the evaluation results are detailed below.

A. SPECTRUM EFFICIENCY

The reuse factor is a major indicator of spectrum efficiency, calculated from the following:

$$\mathrm{RI} = \frac{\mathrm{RA}}{\mathrm{TR}} \tag{2}$$

where RA represents the RBs allotted to cluster heads and independent cars for their V2V/V2I traffic, and TR represents the total RBs in the system.

In Figure 4, we compare the traditional method [15] to our proposed method concerning RI. As can be seen, our proposed method yields a higher RI and, consequently, a higher spectrum efficiency. The best RI is observed when vehicles

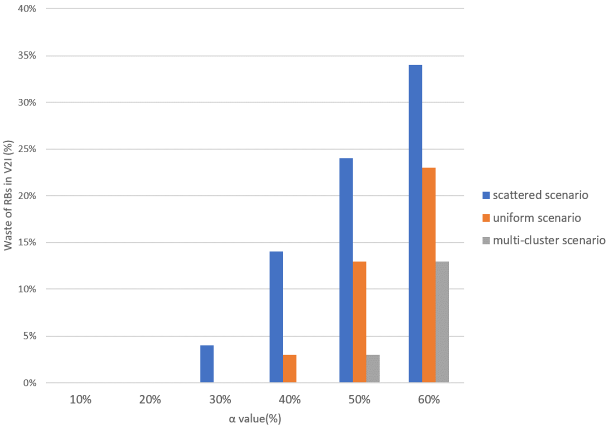

FIGURE 3. Percent of RBs wasted using proposed method versus different values of α.

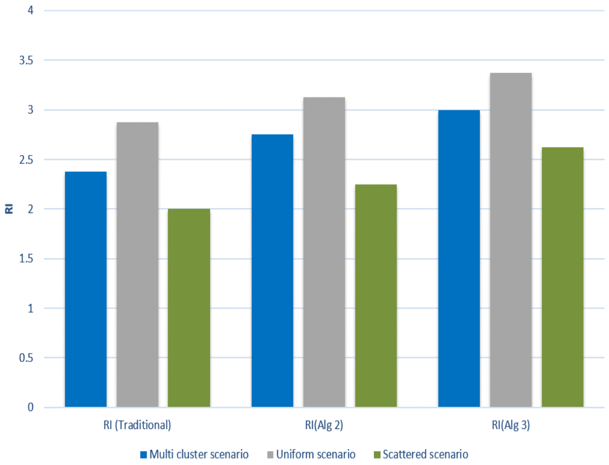

FIGURE 4. Comparison of traditional and proposed methods in terms of RI.

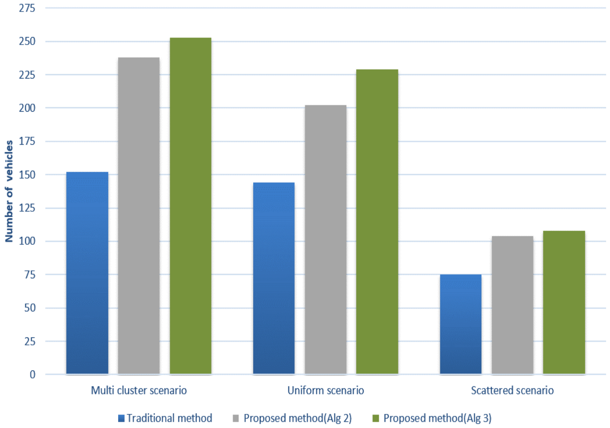

FIGURE 5. Number of supported vehicles (V2V and V2I) using traditional and proposed methods in different scenarios.

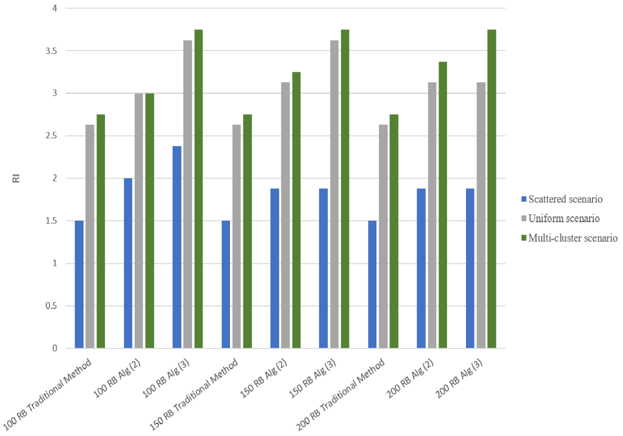

FIGURE 6. Comparing the proposed method to the traditional one in terms of RI versus different values for number of RBs.

are distributed in a uniform manner at all SAs and cluster sizes are extremely similar. Figure 5 compares the number of vehicles supported by the conventional method to those supported by the two proposed algorithms. This figure also illustrates the improved reuse of radio resources, which results in an increased number of supported vehicles. Algorithm 3 yields superior results as it decides in a finer granularity.

Figure 6 compares the proposed algorithms to the traditional one in terms of the RI versus different values for the number of RBs. The figure demonstrates that in limited RBs (100 RBs) case, the RI value shows more growth using the proposed algorithms compared to the traditional method. This means that the proposed algorithms are more suitable for scenarios with higher resource scarcity and lead to support of a greater number of vehicles than baseline. It also is shown that in all settings, Multi cluster scenario has gained the maximum RI. The second algorithm (Algorithm 3) is doing the best to support V2I communications. Figure 7 shows the number of vehicles supported by the proposed algorithms compared to traditional one. This figure also reveals that in the setting with 100 RBs, the proposed algorithms have demonstrated more growth in supported vehicles compared to the baseline. Similar to previous results, the second proposed algorithm shows the best performance.

B. CONNECTION TYPE RATIO (CTR)

The CTR metric represents the percentage of total resources utilized by each communication type. The ratio of exploited RBs for V2I communications is obtained from:

$$\mathrm{CTR}_{\mathrm{V2I}} = \left(\frac{|R_{V2I}|}{|R|}\right) 100\% \tag{3}$$

Here, |R| is the total resource blocks of the BS. The proposed methods exhibit superior performance to the traditional method in this metric. As shown in Figures (8-10), both proposed algorithms have improved the management of C-V2X radio resources. Figures (8-10) illustrate the difference in CTR between traditional and proposed methods in various scenarios, namely scattered, uniform, and

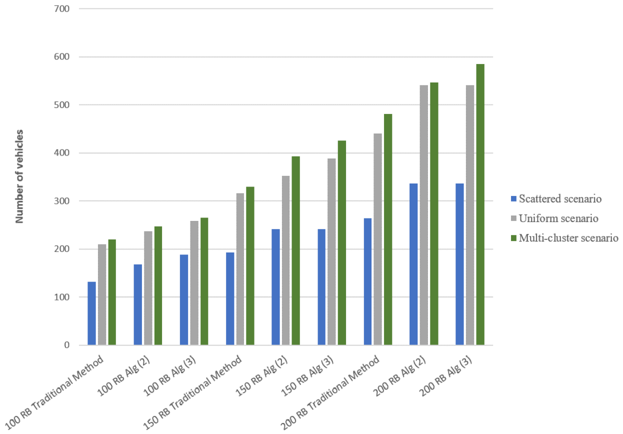

FIGURE 7. **Number of supported vehicles versus different values for the number of RBs.**

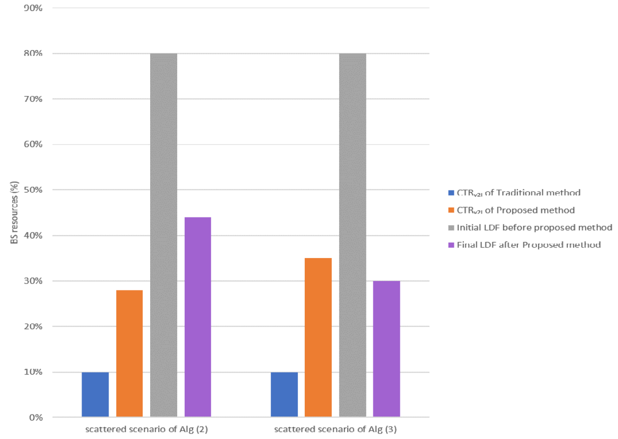

FIGURE 8. **CTR_{V2I} and LDF values in the traditional and proposed methods for the scattered scenario with Alg (2) and Alg (3).**

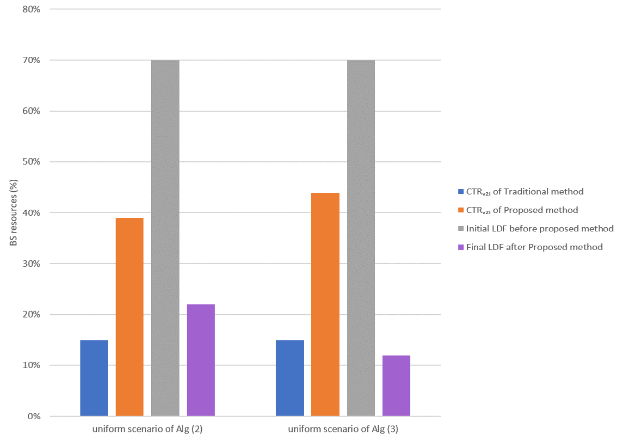

FIGURE 9. **CTR_{V2I} and LDF values in the traditional and proposed methods for the uniform scenario with Alg (2) and Alg (3).**

multi-cluster, respectively. Algorithm 3 shows the best results in this metric, too.

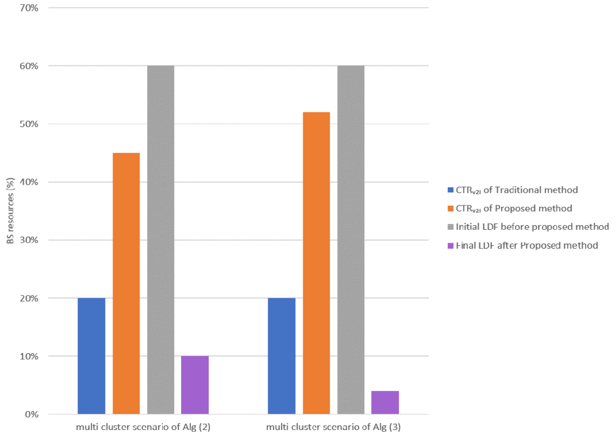

FIGURE 10. **CTR_{V2I} and LDF values in the traditional and proposed methods for the multi-cluster scenario with Alg (2) and Alg (3).**

Figures (8, 9, 10) examine the performance of the proposed method within scattered, uniform, and multi cluster scenarios, respectively. In these figures, load difference (LDF) represents the difference between the percentage of resources utilized by V2I and V2V communications before and after executing the proposed algorithms. The initial α value for each scenario is determined based on Table (2).

Based on these results, our method is vastly preferred over the conventional approach for increasing network sum rate (spectrum efficiency) at V2I links. We have observed that the algorithms being proposed not only focus on efficiently utilizing resources, but also aim to minimize wastage. Algorithm 2 allows the entire low load SRs to be used by V2I links which may result in transferring more than what is actually required. To address this issue, Algorithm 3 comes into play which only transfers the necessary amount of unused part of the SR. Therefore, this ensures that only the required number of resources are utilized and any excess or wastage is minimized. Algorithm 2 provides a greater improvement than conventional method and Algorithm 3 gives the best improvement in all scenarios based on the performed comparisons. The proposed method provides the greatest improvement in multi-cluster scenario (Figure 10). Overall, we observe from the various scenarios that the demand for unused RBs increases as the number of clusters increases. Therefore, the multi-cluster area is the most demanding scenario that must be supported by unused V2V communication resources, whereas our method provides superior performance to satisfy both V2V and V2I communications in this scenario.

Since both algorithms stand for borrowing free RBs of the SRs (the RBs which are currently unallocated), it is evident that the signal-to-interference ratio (SIR) of V2V links remains unchanged. Also, those RBs will only be used once for each V2I link in the cell; therefore, there is no possibility of degrading the SIR of V2I links.

VI. CONCLUSION

Vehicle-to-everything (V2X) communications are receiving increased attention from 5G wireless networks as the number of autonomous vehicles on the road rises. Due to the limited licensed radio resources in 5G cellular networks, cellular V2X has difficulty managing network access for a large number of vehicles. This study focuses on the difficulty posed by limited radio resources for V2I applications with vital V2V safety applications. This method assumes geo-based RA to manage V2V communications' resources, while cluster-based routing is considered for V2I communications using DSRC. We present a routing-aware radio resource management algorithm that manages V2V communication resources regarding the requirements of clusters constructed during routing. The first algorithm adopts lending unused V2V resources to CHs in terms of sub-resource pools if the quality of V2V communications is preserved. The second algorithm is capable of lending unused RBs from V2V sub-resource pools. The simulation results demonstrate that the proposed algorithms achieve a significant increase in spectrum efficiency over the conventional method without compromising the quality of V2V communications. As seen, the second proposed algorithm shows higher spectrum efficiency than the first one, at the expense of violating the SR-based rule of resource partitioning in geo-based V2V resource allocation scheme. Future work will include extending the proposed method to multi-cell scenario and considering routing-awareness in RA of other VANET scenarios. Moreover, mathematical modeling and analysis of the proposed idea and presenting more intelligent solutions for the stated problem are suggested as future work.

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