Towards a Resource-Aware K-Selection Model for Optimizing V2X Communication in Autonomous Vehicles

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Abstract **- The rise of autonomous vehicles is accompanied by the emergence of bandwidth-intensive applications like real-time 3D map downloads, necessitating improved bandwidth utilization. While clustering has proven effective in prior research to partially address this challenge, existing works often assume a perfect cluster formation without accounting for outliers, and the selection of the number of clusters (k) tends to be resource-agnostic. This paper presents the preliminary findings from the initial cluster analysis phase, laying the foundation for a resource-aware k-selection model. This model aims to optimize bandwidth resources and alleviate throughput bottlenecks between Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) links. The cluster analysis part of our work examines the variation in sizes of various vehicular cluster components concerning changes in cluster range (dth) and the number of clusters (k). Notably, our approach considers unclustered vehicles, acknowledging their impact on bandwidth utilization. Our results reveal a consistent pattern and correlation between the size of different vehicular components and the variables considered (k and dth). Drawing insights from this understanding of vehicular cluster behaviour, we propose an approach to optimize V2I and V2V bandwidth usage while minimizing throughput bottlenecks between V2V and V2I links. This resource-aware k-selection model holds the potential to significantly enhance the efficiency and performance of Vehicle-to-Everything (V2X) communication in the era of autonomous vehicles, contributing to the realization of a seamless and high-throughput vehicular communication network.**

Keywords-Cluster; bandwidth; V2X; V2V; sidelink.

I. INTRODUCTION

Clustering approaches has gained significant interest in V2X research in recent years, and this is due to the potential it holds with regards to mitigating stability issues emanating from the dynamic characteristic of vehicular network topology as demonstrated in the works in [1]-[4]. However, with the increasing growth in autonomous driving, accompanied with rise in data-intensive driving applications and use cases has raised questions concerning the quality of vehicular links and their capacity to cope with these emerging applications. Cluster-based approaches has been suggested to improve link performances either by shortening of link length, resource allocation or by hot-spot based relaying. Though cluster-based relaying has been touted to minimize bandwidth resource contention in Cellular-V2X (C-V2X) [4][5], and cluster-based resource allocation have been suggested to maximize resource utilization [6][7], the potential of these approaches can be limited by a little considered factor. Outlying or unclustered vehicles. Also, it is unrealistic to continuously minimize cluster threshold to minimize link length, as this could either indiscriminately increase number of clusters or number of unclustered vehicles.

We seek an approach that could exploit the optimal selection of number of clusters to consolidate on the resource gains potential of cluster-based relaying and resource allocation.

Most approaches of selecting number of clusters (k) are resource agnostic and have only considered the compactness of clusters [8]-[12]. For example, the gap method described in [12] compares cluster compactness value with a null reference point. The popular elbow method described in [10] uses a visual observation to select an edge point at which within-cluster-sum of squared error difference starts to diminish. Calinski-Harabasz [8], David Bouldin [9] and Silhouette [11] approaches all considered both intra-cluster compactness and inter-cluster separation. All these approaches though have been used in clustering process of vehicular nodes in V2X networks and Vehicular ad hoc Networks (VANETs), they are all resource agnostics and have little consideration for unclustered vehicles.

Our approach focusses on building on the idea of cluster-based relay and resource allocation to further optimize utilization of V2X bandwidth resources by selecting optimal number of clusters (k) with consideration for available resources, free vehicles, and cluster boundary threshold. The goal is to maximize the use of both V2I and V2V bandwidth resources. We approach the conundrum by first analysing the relationship between the variables considered, then find a solution that minimizes the V2I links and maximum cluster size, which in turn maximizes the resources available to both V2I and V2V users. The analysis is done in the context of mode-3 centralised resource allocation, where separate dedicated resources are allocated for V2I and V2V communication. The results obtained from the analysis demonstrates a specific pattern of variation of number of V2I users along changes in number of clusters and distance threshold which suggest an understanding that for a dedicated allocation approach there exist a point where the minimum number of V2I users will offer the maximum V2I bandwidth. A similar observation is observed for V2V users with respect to maximum cluster size variation. Having, completed the analysis, we proceeded to develop an optimization problem to maximize bandwidth utilization. that the optimal number of cluster (k) solution and cluster boundary threshold that yields the maximum bandwidth/user.

The rest of this paper describes in detail the cluster analysis and the proposed optimization. In Section 2, a description of the overall system model is presented, which includes the cluster and resource allocation model. Section 3 presents the cluster analysis, describing variations across number of clusters and distance threshold. Section 4 presents the proposed k-selection optimization model while Section 5 concludes the paper.

II. SYSTEM MODEL

The consideration of cluster-based relay necessitates a description of the topology and the communication model underpinning the topology. The topology is developed in the context of a 2-hop downlink transmission path proposed for download of urgently needed real-time traffic data. Vehicles are grouped into clusters where the Cluster Heads (CHs) serve as a relay and a download hotspot for the rest of Cluster Members (CMs). The 2-hop downlink transmission path consist of the cluster backhaul or the Base Station to Cluster Head downlink (BS-to-CH) and the Cluster Head to Cluster Member (CH-to-CM) sidelink. The CH-to-CM V2V side links are modelled in an urban environment as described in [13]. The pathloss and shadowing model we employed for the backhaul is based on the channel model defined in [14].

Concerning interference, we used different interference schemes for the V2I/N links and the V2V sidelink. For the V2I/N links, we adopted frequency reuse of 1 and hexagonal cell coverage with the BS at the centre of the hexagon. We assume a variation of Fractional Frequency Reuse (FFR) is used by the base station to allocate resources to the V2I/N nodes/links. We have decided to limit our discussion about the type or implementation of the FFR scheme, since the type of scheme adopted has no impact on the downlink interference considered in our scenario.

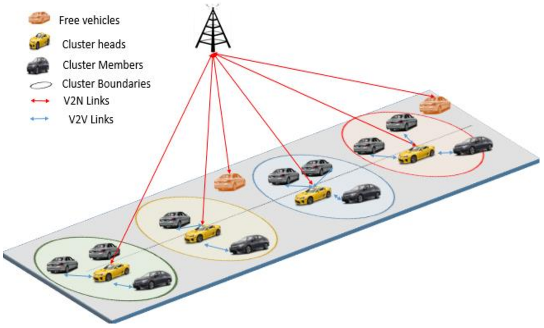

Figure 1. System Model of Cluster Based C-V2X.

For the V2V sidelink, the frequency allocation and interference are cluster-based. A typical vehicular node uses a different channel from those used by its co-cluster members and same bandwidth channel to CMs of other clusters that poses least interference. A simple depiction of the interference and resource allocation approach used is depicted in Figure 2. The coloured bar at the top represents the entire resource allocated for V2V sidelink communication, while each colour represents the equal bandwidth resource blocks allocated to each V2V CH-to-CM sidelink. The dotted lines represent interference while the continuous lines represent received signal link. Note that the resource bar has size different colours, each colour represents the resource blocks attached to each user and the size of each block is defined by the maximum cluster size, $C_{sz(max)}$.

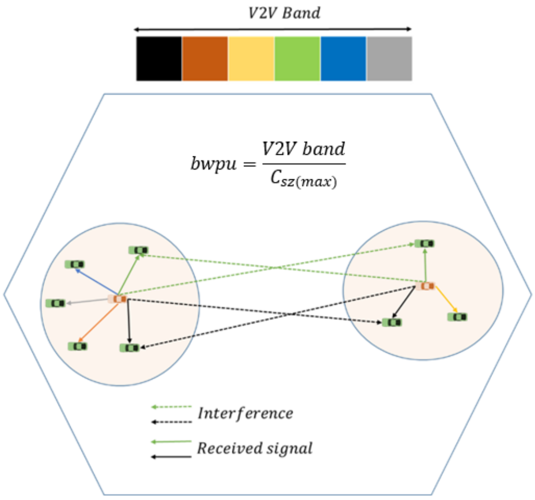

Figure 2. A Depiction of Interference Coordination and Resource Allocation for V2V Sidelink Communication.

III. CLUSTER ANALYSIS

In effort to maximize bandwidth per user-link and minimize the potential bottleneck between V2I and V2V links along relay transmission path, we seek to investigate the variation of the sizes of different vehicular node components with changes in cluster boundary thresholds and number of clusters.

The resource assignment used in this model assumes a dedicated resource slice for C-V2X, with a further dedicated and distinct bandwidth resource to V2I and V2V links. Our approach to optimizing the use of the V2I bandwidth resource per user link and reducing the cluster backhaul bottleneck is by minimizing the number of V2I user links contending for the resource. Likewise, for maximizing the V2V side-link resource per user link, we approach this by minimizing the maximum cluster size at each clustering instance, building on our V2V resource allocation scheme described in Section II. To do this, a study of the relationship between the number of different vehicle designation (CH, CM and FV) and cluster parameters, such as the number of clusters and cluster distance thresholds needs to be explored.

Our study shows how the number of V2I, and maximum cluster size varies with different cluster radius threshold and different number of clusters. In Figure 3, we present a plot of the average number of V21 users across different k-values against a varying distance threshold between 300m to 1000m.

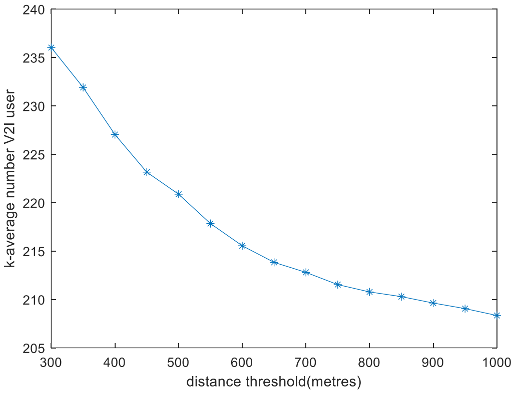

Figure 3. Average Number of V2I User Links across Number of Clusters vs Distance Threshold.

Figure 3 indicates that the number of V2I users drops with increasing distance threshold range being considered, with a total variation of 27 users across threshold range. The minimum number of V2I users is observed at the maximum threshold, implying that this point potentially meets the requirement of minimizing the number of users contending for V2I bandwidth resources.

The plot in Figure 4 shows the variation of average number of V2I users across distance against number of clusters. The number of clusters considered ranges across the total number of vehicles, from 1 to 400. It is observed that at just one cluster, the average number of V2I vehicles across distance threshold is approximately 375, which is essentially the total number of vehicles less the number of CMs in the cluster. This means we have an average of 25 CMs in the first clusters across distance threshold and the total number of free vehicles is around 374, which represents the total number of V2I vehicles less the CH of the single cluster.

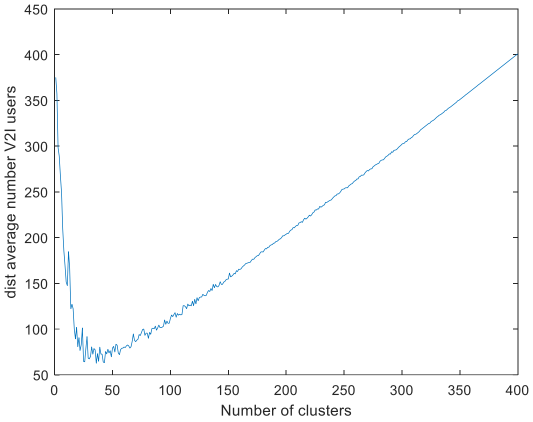

Figure 4. Plot of Average Number of V2I User links Across Distance Threshold Vs Number of Clusters.

However, as the number of clusters increase, the number of V2I vehicles and links drops until a point is reached where a further increase in the number of clusters increases the number of V2I vehicles or links. This points (number of clusters, number of V2I user links) is reached at approximately (36, 66). From this point onwards there is an almost linear increase I the number of V2I user links with number of clusters, until a point where every individual vehicle is a CH of its own cluster at (400,400).

A 3D-plot showing a comprehensive variation of V2I along distance threshold and number of clusters is presented in Figure 5.

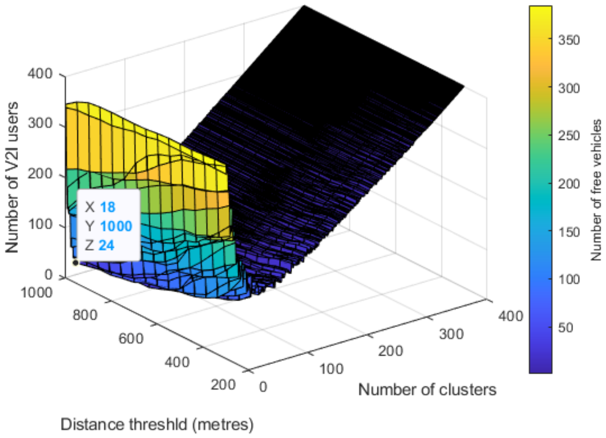

Figure 5. Surface Plot Showing Variation of V2I and FV User Links Across Distance Threshold and Number of Clusters.

It also shows the variation of number of free vehicles links within the number V2I user links. The FV links continues to decrease across increasing number of clusters and increasing distance threshold.

The minimum number of V2I users is obtained at 18 clusters and 1000m of cluster distance threshold. At this point the number of free vehicles, 6 is the total number of V2I user links, 24 less the number of clusters, 18.

For the CH-to-CM V2V side-links, it is understandable that the number of side-links is the total number of vehicles less the CHs and FVs. But one important parameter in the V2V side-link context is the maximum cluster size, which defines the number of side-links or the number of CMs in the most populated cluster. The importance is particularly related to how resource allocation is done in our V2V resource reuse scheme described in Section II. The resources allocated to each CH-to-CM side-link is directly determined by and inversely proportional to maximum cluster size. Figure 6 shows how average maximum cluster size across distance threshold behave in response to changes in the number of clusters. As number of clusters increases, the average maximum cluster size over all distance threshold considered increases, until a specific number of clusters is reached (in this case about 8 clusters). At this point, a further increase in the number of clusters reduces the maximum cluster size achievable until a point where the number of clusters equals the number of nodes in context, at which point cluster size is 1 and at minimum.

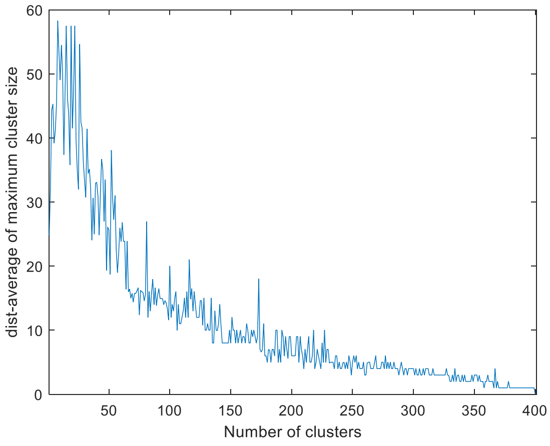

Figure 6. Plot of Average Maximum Cluster Size across Distance Threshold Vs Number of Clusters.

Figure 7, on the other hand, presents the variation of average maximum cluster size across number of clusters against distance threshold.

The plot clearly indicates that the maximum cluster size increases with increasing distance threshold, however compared to the variation across number of clusters, it is observed that the changes in maximum cluster size here is relatively small, with a total variation of less than 3 vehicles as compared to a maximum cluster size variation of approximately 57 vehicles observed in Figure 6.

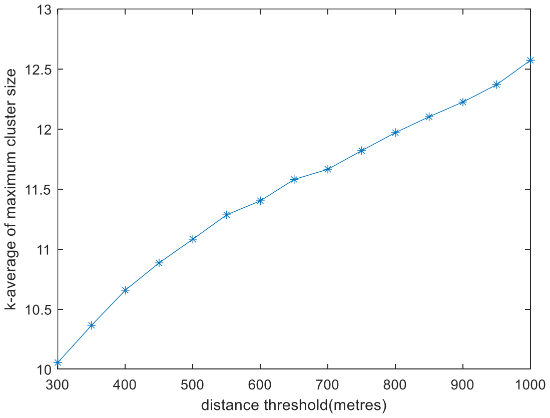

Figure 7. Plot of Average Maximum Cluster Size across Number of Clusters Vs Distance Threshold.

The investigation extends beyond the mere comprehension of the dynamics exhibited by distinct components within vehicular nodes in response to variations in distance thresholds and number of clusters. The outcomes gleaned from this analysis offer valuable indications for the strategic optimization of bandwidth resource utilization and the amelioration of potential bottlenecks in cluster backhaul.

IV. PROPOSED OPTIMAL-K PROBLEM

Our aim is to maximize the bandwidth available to both V2I and V2V links and potentially minimize throughput bottleneck along relay transmission path. Unlike traditional k-selection schemes, we seek to understand the relationship between the k-value, number of unclustered vehicles and how they affect the bandwidth resources at the disposal of V2I and V2V links.

For each number of clusters, $\mathrm{k_x}$ ranging across the entire number of vehicles as described by the set, K in equation (1) , the corresponding centroid positions are evaluated using k-means and k-means++.

$$\mathrm{K} = \{\mathrm{k_x}: 1 \le \mathrm{x} \le \mathrm{n}\} \tag{1}$$

For each value of $\mathrm{k_x}$, considering a superset, Z comprising of a set of Signal-to-Noise Ratio (SNR) values, ζ_t. Each set, ζ_t comprises of evaluated SNR values between each vehicle $\mathrm{V_t} \in \mathrm{V}$ and all centroids, i as defined in equations (2), (3) and (4) and each cluster has a corresponding cluster head, $\mathrm{Ch_i}$ as in equation (5)

$$\mathrm{Z} \sqsupseteq \{\zeta_\mathrm{t}: 1 \le \mathrm{t} \le \mathrm{n}\} \tag{2}$$

$$\mathrm{V} = \{\mathrm{V_t}: 1 \le \mathrm{t} \le \mathrm{n}\} \tag{3}$$

$$\zeta_\mathrm{t} = \{\zeta_\mathrm{i}: 1 \le \mathrm{i} \le \mathrm{k_x}\} \tag{4}$$

$$\mathrm{C} = \{\mathrm{c_i}: 1 \le \mathrm{i} \le \mathrm{k_x}\} \tag{5}$$

where n is number of vehicles, V is a set of all vehicles, $\mathrm{k_x}$ represents the number of centroids, t represents the index of specific vehicle and i is the index of a specific cluster, CH, or centroid.

Also, we consider a set of distance thresholds defining the radius within which clusters are bounded to be $\mathrm{d_{th}}$, we define a set of SNR threshold, $\mathrm{SNR_{th}}$ as a function of $\mathrm{d_{th}}$ as described in Equation (6). Where the function is based on sidelink pathloss, Received Signal Strength (RSS) and noise.

$$\mathrm{f}(\mathrm{d_{th}}) \rightarrow \zeta_\mathrm{th} \tag{6}$$

Having estimated ζ_th, we associate each vehicle to centroids with which the vehicle has maximum SNR, ζ_t and whose ζ_t is below the threshold. For every value of $\mathrm{k_x}$ number of centroids, we have cluster identities ranging from 1 to $\mathrm{k_t}$ and mapped to each vehicle and saved as a set of vehicle cluster identity, $\mathrm{C_L}$ as presented in equation (7) with the size of each cluster, $\mathrm{C_s}$ defined in equation (8). The maximum cluster size, $\mathrm{C_{max}}$ is identified and the number of free vehicles, $\mathrm{F_v}$ is evaluated as presented in equations (9) and (10).

$$\mathrm{C_L} = \underset{1\le \mathrm{t} \le \mathrm{n}}{\overset{\forall}{}}\zeta_\mathrm{t} \left\{ \underset{1 \le \mathrm{i} \le \mathrm{k_x}}{\operatorname{argmax}} (\zeta_\mathrm{t} \ge \zeta_\mathrm{th}, \mathrm{c_i}) \right\} \tag{7}$$

$$\mathrm{C_L} = \{\mathrm{C_t}: 1 \le \mathrm{t} \le \mathrm{n}\}$$

$$\mathrm{C_s} = \{\mathrm{C_{si}}, 1 \le \mathrm{i} \le \mathrm{k_x}: \mathrm{n}(\mathrm{c_i} \in \mathrm{C_L}\} \tag{8}$$

We then exploit the variation in number of CHs, number of FVs and maximum cluster size, $\mathrm{C_{max}}$ with the distance threshold and number of clusters to maximize the bandwidth available per V2I and V2V link. Both $\mathrm{C_{max}}$ and $\mathrm{F_v}$ are estimated as presented in equations (9) and (10), respectively.

$$\mathrm{C_{max}} = \max\{\mathrm{C_s}\} \tag{9}$$

$$\mathrm{F_v} = \mathrm{n} - \sum_{\mathrm{i}=1}^{\mathrm{k_x}} \mathrm{C_{si}} \tag{10}$$

Recalling resource allocation approach, where V2V and V2I links are allocated distinct dedicated frequency band and V2I bands are dedicated and separate from bands used by other BS users, we have decided to approach k-selection in a way that maximizes usage of both V2V and V2I bandwidth resources per link. This approach seeks to keep the bandwidth allocated to V2I and V2V as close as possible with the bandwidth allocated to V2I links greater than the bandwidth allocated to V2V side links. The optimization problem is defined in equations (11) to (17), with the multi-objective functions are presented in equations (11) and (12), while the constraints are presented in equations (14) to (17).

$$\frac{B_{v2i}}{k_x + F_v} + \frac{B_{v2v}}{C_{max}} \quad Maximize \tag{11}$$

$$\frac{B_{v2i}}{k_x + F_v} - \frac{B_{v2v}}{C_{max}} \quad Minimize \tag{12}$$

The first objective function presented in the optimization expression in (11) seeks to maximize the combined bandwidth per V2I and V2V link, consequently seeking to reach a compromise between the number of V2I links and cluster size. While maximizing the bandwidth per user link, the second objective function presented in the optimization expression in (12) seeks to minimize the difference between V2I and V2V bandwidth per user link. The aim is to prevent excessive skewing of bandwidth towards V2I, which could in turn portend redundant throughput at the backhaul.

We then combine the objective functions to a single super objective function which when maximized, its optimal solution is used to find the maximum combine V2I and V2V bandwidth per user-link. The super objective function is expressed in (13).

$$\frac{B_{v2i}}{k_x + F_v} + \frac{B_{v2v}}{C_{max}} - \left(\frac{B_{v2i}}{k_x + F_v} - \frac{B_{v2v}}{C_{max}}\right) \quad Maximize \tag{13}$$

The objective functions are constrained by the conditions expressed in the inequalities between (14) and (17). The first inequality presented in (14) limits the V2V and V2I optimal bandwidth pair to a pair that where V2I bandwidth is greater than V2V bandwidth. The reason for this is to guarantee some performance reliability for CH's V2I links that shoulders relaying responsibility. A performance issue for CH V2I links has a multiplier effect on CMs. The constraint in (15) limits the k-selection solution to a range number of clusters within which the condition that V2V bandwidth per user link can only be as big as V2I link bandwidth per user can be satisfied. This is useful to keep the number of clusters within the range that sustains the proximity advantage defined by traditional k-selection methods. Here, we used a quantitative silhouette-based elbow method similar to the approach used in [15]. The inequality in (16) and (17) constrains the objective functions to values where k_x and C_{max} is greater than 1 and to values where $B_{v2i}, B_{v2v}, \mathrm{k_{elb}}$ and $\mathrm{F_v}$ is non-zero. This is to exclude extremities from solution options.

$$\frac{\mathrm{B_{v2i}}}{\mathrm{k_x} + \mathrm{F_v}} \geq \frac{\mathrm{B_{v2v}}}{\mathrm{C_{max}}} \tag{14}$$

$$\mathrm{k_{elb}} + 2 \geq \mathrm{k_x} \geq \mathrm{k_{elb}} \tag{15}$$

$$\mathrm{k_x}, \mathrm{C_{max}} > 1 \tag{16}$$

$$\mathrm{B_{v2i}}, \mathrm{B_{v2v}}, \mathrm{k_{elb}}, \mathrm{F_v} > 0 \tag{17}$$

Here, $\mathrm{B_{v2i}}$ is the total bandwidth resource allocated for V2I communication, $\mathrm{B_{v2v}}$ is the total bandwidth resource allocated for V2V communication and $\mathrm{k_{elb}}$ is the optimal k-value as estimated using the quantitative elbow method.

V. CONCLUSION

This research addresses the critical challenges arising in the V2X communication landscape, particularly within the context of autonomous vehicles. The preliminary findings presented herein underscore the significance of a resource-aware approach to the selection of the number of clusters (k) in vehicular networks. Existing clustering methodologies, while effective, often overlook the presence and impact of unclustered or free vehicles, thus necessitating a more comprehensive analysis.

Through a meticulous investigation of the dynamics within vehicular clusters, considering variations in cluster range (dth) and the number of clusters (k), this study reveals consistent patterns and correlations between the number of vehicular components and the variables. Noteworthy insights have emerged, indicating that within a dedicated resource allocation approach, there exist points across the different variables where V2I and V2V bandwidth can be maximized.

The proposed resource-aware k-selection model, rooted in these findings, holds substantial promise for enhancing the efficiency and performance of V2X communication. By optimizing the utilization of bandwidth resources and mitigating potential bottlenecks, this model contributes to the realization of a seamless and high-throughput vehicular communication network. Future work will delve deeper into the optimization problem presented, refining the model, and validating its efficacy through simulations and real-world implementations. This research seeks to propel advancements in V2X communication, aligning with the transformative potential of autonomous vehicles in reshaping the landscape of transportation efficiency and safety.

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