IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 8 June 2026, accepted 6 July 2026, date of publication 13 July 2026, date of current version 21 July 2026.

Digital Object Identifier 10.1109/ACCESS.2026.3712589

RESEARCH ARTICLE

Non-Negotiated Implicit ETSI VAM Clustering

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This work was supported in part by the Excellence Center at Linköping-Lund in Information Technology (ELLIIT) network through the Project 6G-V2X "6G Wireless, Sub-Project: Vehicular Communications", and in part by Swedish Transport Administration through the Project "Here I go"—avancerade funktioner för VRU-medvetenhetsprotokoll i C-ITS under Grant TF 2023/104170.

ABSTRACT Including Vulnerable Road Users (VRUs) such as pedestrians and cyclists in Cooperative Intelligent Transport Systems (C-ITS) is key to improving road safety, but it also increases the number of active communication nodes and, as a result, the channel load. In dense scenarios, this can lead to congestion, increased contention, and reduced reliability in Vehicle-to-Everything (V2X) communications. Clustering has been proposed as a way to address this issue by allowing a single node to represent multiple VRUs. However, the clustering scheme defined by European Telecommunications Standards Institute (ETSI) relies on explicit negotiation and in-cluster communication, which introduces additional signaling and assumes reliable message exchange. In this paper, we propose an implicit clustering mechanism for VRU Awareness Messages (VAMs) that removes the need for explicit coordination between nodes. Instead, clusters emerge directly from regular broadcast messages, without additional negotiation or maintenance signaling, and remain robust even under lossy communication conditions. Simulation results show that the proposed approach reduces channel load by approximately 20% compared to the ETSI clustering scheme while achieving higher VRU awareness levels that are comparable to standalone operation.

INDEX TERMS Intelligent transportation systems, bicycles, pedestrians, connected vehicles, vehicle-to-everything.

I. INTRODUCTION

The protection of VRUs, such as pedestrians and cyclists, is a key objective of C-ITS. To support this goal, standardization bodies such as ETSI have defined communication services that allow VRUs to share their position and motion information with nearby vehicles. In particular, the Vulnerable Road User Awareness basic service (VBS) enables VRUs to broadcast VAMs, allowing surrounding road users to detect their presence and update local dynamic maps.

As the number of connected VRUs increases, however, the wireless channel may become congested due to the large number of periodic awareness messages. V2X messages are not always reliably delivered under high channel load, since medium contention and packet losses can affect both reliability and information freshness [1]. This problem becomes particularly relevant in dense urban environments, such as bicycle corridors, pedestrian crossings, intersections, roundabouts, and shared mobility areas, where many VRUs may be located close to each other and broadcast at the same time.

Previous work has addressed this problem from different perspectives. Early studies evaluated the communication performance of pedestrian and VRU safety applications under different traffic and radio conditions [2], [3], [4]. More recent work has investigated adaptive message generation strategies to reduce channel load while preserving tracking accuracy [5], [6], [7]. In parallel, clustering-based approaches have been studied as a way to reduce redundant transmissions in dense VRU scenarios [8], [9], [10]. These works show that reducing redundant awareness information is important for scalability, but they also leave open the question of how clustering can be achieved with minimal coordination overhead.

The ETSI VBS specification addresses redundancy through a clustering mechanism in which nearby VRUs

The associate editor coordinating the review of this manuscript and approving it for publication was Angelo Trotta.

with similar motion are represented by a cluster leader. The leader periodically broadcasts coverage information on behalf of the group, potentially representing between 3 and 20 VRUs within a radius of approximately 3–5 m. Although cluster members suppress their own VAM transmissions, they must still exchange control information to join, maintain, or leave the cluster. These operations may occur either in-band over the V2X channel or through out-of-band technologies such as Bluetooth, and the ETSI specification defines signaling procedures to manage cluster membership and state transitions [11, 5.4.2].

This introduces a practical challenge. A clustering mechanism should reduce redundant transmissions, but the coordination needed to create and maintain the cluster can itself consume channel resources and depend on reliable message exchange. In dense or lossy environments, negotiation messages may be delayed or lost, cluster membership may change quickly, and additional signaling can increase the same contention that clustering is intended to reduce. Thus, the problem addressed in this paper is how to reduce redundant VAM transmissions while preserving awareness, using only regular broadcast messages and without requiring explicit negotiation or in-cluster communication.

This paper proposes an implicit clustering mechanism for VAMs. Instead of negotiating cluster membership, nodes infer their role from regular broadcast messages and dynamically decide whether to operate as standalone transmitters, cluster leaders, or covered cluster members. The mechanism does not require explicit join, leave, or membership confirmation procedures, and avoids additional in-band or out-of-band in-cluster communication.

To evaluate the proposed approach, we compare the expected channel usage of standalone VAM transmissions with both the ETSI clustering scheme and the proposed implicit clustering mechanism. While the mechanism is applicable to different types of VRUs, the evaluation considers both pedestrian and bicycle scenarios in order to capture different mobility dynamics and message generation patterns.

The main contributions of this work can be summarized as follows:

- We propose a non-negotiated implicit clustering mechanism for ETSI VAMs, in which nodes infer their role from regular broadcast messages and transition between standalone, leader, and covered-member behavior without explicit join, leave, membership confirmation, or in-cluster communication procedures.
- We evaluate the proposed mechanism through analytical modeling and network simulations against standalone VAM transmissions and the ETSI-standard clustering mechanism, showing that it reduces message generation and channel load while maintaining VRU awareness in dense traffic scenarios.

The remainder of the paper is organized as follows. Section II reviews related work on VRU communication and clustering mechanisms. Section III presents the technical background of ETSI VAM clustering. Section IV introduces the proposed implicit clustering scheme. Section V evaluates its performance through analytical modeling and network simulations. Section VI discusses the implications and limitations of the results, and Section VII concludes the paper.

II. RELATED WORK

Several studies have investigated the scalability and reliability of VRU communication. Early work focused mainly on pedestrian safety applications, evaluating metrics such as packet delivery ratio, latency, and communication range under different traffic conditions [2], [3], [4]. More recently, cooperative VRU protection schemes based on VAM have also been evaluated in realistic C-ITS environments [12].

Another line of work has focused on adapting message generation to reduce channel load while preserving tracking accuracy. Martín-Pérez et al. [5] studied optimal sampling policies for pedestrian awareness messages, showing that adaptive transmission intervals can reduce channel use without significantly degrading positioning accuracy. Similar trade-offs have been studied for electrically assisted bicycles and pedelecs, where VAM generation dynamics directly affect message frequency, channel load, and awareness accuracy [6], [13]. Ostendorf et al. [7] further evaluated redundancy mitigation in bicycle VAMs, highlighting the relevance of suppressing unnecessary VRU awareness traffic.

These approaches improve communication efficiency at the message-generation level, but they do not fully address the redundancy caused by multiple neighboring VRUs broadcasting correlated state information. Such redundancy can significantly increase channel load in cooperative V2X systems [14]. It can also affect the freshness of received information, since channel contention and packet losses increase the delay between message generation and reception. This connection has been studied through the concept of Age of Information (AoI), with Baiocchi et al. [1] showing that contention and packet loss strongly affect the timeliness of broadcast information in IEEE 802.11p vehicular networks.

To mitigate this redundancy, clustering mechanisms have been introduced within the ETSI VBS specification [11]. In this framework, nearby VRUs with similar motion characteristics may form a cluster in which a designated cluster leader periodically broadcasts information representing the group. Cluster members suppress their own transmissions while remaining covered by the leader's broadcast. This reduces the number of individual VAM transmissions, but cluster formation and maintenance are handled through explicit signaling procedures, including join requests, confirmation messages, and periodic keep-alive transmissions.

Several studies have investigated clustering-based approaches for VRU communication. Lobo et al. [8] analyzed clustering strategies for groups of cyclists communicating via V2X technologies, showing that clustering can reduce channel utilization in dense scenarios. Xhoxhi et al. [9] proposed geometric aggregation techniques to efficiently represent multiple VRUs within Collective Perception Messages (CPMs) while controlling the size of the representation.

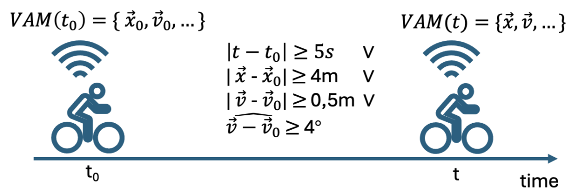

FIGURE 1. VAM generation conditions.

This is closely related to the scalability problem addressed in this paper, but it follows a different design direction, since it relies on CPMs rather than on standard VAMs. More recently, Lobo et al. [10] evaluated the VBS clustering mechanism in a large-scale multimodal VRU scenario, showing that clusters are mainly formed in high-density areas and that cyclist clustering remains challenging under realistic mobility conditions.

Therefore, a clear gap remains in the existing literature. Adaptive message generation schemes improve communication efficiency but do not address the group-level information redundancy problem. Meanwhile, current clustering solutions address this issue, but either rely on explicit coordination to form and maintain clusters, or use additional message structures to represent VRU groups. In dense or lossy broadcast environments, these mechanisms may introduce overhead and increase the dependence on reliable message exchange. Motivated by this limitation, this work proposes an implicit clustering mechanism in which clusters emerge directly from regular VAM broadcasts, without negotiation, membership management, or dedicated cluster-control messages.

III. ETSI VAM CLUSTERING

A. VAM MESSAGE GENERATION

The ETSI defines the VBS to support cooperative awareness among road users such as pedestrians and cyclists. The service relies on the periodic broadcast of VAMs, which convey information about the position, movement, and status of VRUs. These messages enable nearby vehicles and infrastructure nodes to detect and track vulnerable users, thereby supporting safety applications.

Rather than being transmitted at a strictly fixed rate, VAMs are generated when significant changes in the VRU's motion state occur. Specifically, a VRU device periodically evaluates whether variations in position, speed, or heading exceed predefined thresholds. If any of these conditions is satisfied, a new VAM is generated and broadcast.

Fig. 1 summarizes the triggering logic used for VAM generation. Every 0.1 s, the VRU device evaluates the triggering conditions; if at least one threshold is exceeded, a VAM is transmitted. Otherwise, transmission is deferred until the next evaluation cycle.

B. ETSI CLUSTERING MECHANISM

In dense scenarios where multiple VRUs are located in close proximity, the transmission of individual VAMs by each device may lead to increased channel load and reduced communication efficiency. To mitigate this issue, the ETSI specification introduces a clustering mechanism in which a single node represents multiple VRUs by transmitting aggregated VAMs information on their behalf. This approach reduces the number of transmitted messages while maintaining situational awareness for nearby road users.

The ETSI clustering mechanism relies on explicit signaling procedures to establish, maintain, and dissolve clusters. Nodes exchange control information through dedicated containers within VAMs to coordinate cluster membership and leadership. A cluster is formed when one node assumes the role of *cluster leader*, while neighboring nodes join the cluster as *members*. The leader is responsible for broadcasting VAMs that include information about all cluster members.

C. CLUSTER FORMATION

Cluster formation occurs when a node determines that it can act as a cluster leader for nearby VRUs. The decision is typically based on proximity and communication conditions. The node initiating the cluster advertises its intention to serve as leader through information contained in its VAM transmissions.

Neighboring nodes receiving this information evaluate whether they satisfy the conditions required to join the cluster. If the conditions are met, the nodes transition from standalone mode to the *cluster member* state. Once part of the cluster, members stop transmitting their own individual VAMs and rely on the leader to represent them in aggregated VAM transmissions.

This explicit negotiation process ensures that cluster membership is coordinated among nodes, but it also introduces additional signaling overhead.

D. CLUSTER MAINTENANCE

Once established, clusters must be maintained as long as the spatial and communication conditions that justified their creation remain valid. Cluster members continuously monitor the VAMs transmitted by the cluster leader to confirm that they are still represented within the cluster.

The cluster leader periodically updates the aggregated information about cluster members and broadcasts this information through its VAMs. These updates allow nearby vehicles and infrastructure nodes to maintain awareness of all VRUs represented by the cluster.

Because cluster maintenance relies on explicit coordination between nodes, additional signaling information must be exchanged to ensure that cluster membership remains consistent.

E. CLUSTER DISSOLUTION

Clusters are dissolved when the conditions that enabled their formation are no longer satisfied. This may occur when members move outside the communication range of the leader, when mobility dynamics cause the group to disperse, or when communication losses prevent reliable coordination.

In such cases, nodes transition back to the standalone state and resume transmitting their own VAMs. Explicit signaling procedures are used to notify cluster members about the termination of the cluster.

The behavior of the ETSI clustering mechanism is defined through a state machine illustrated in Fig. 2. The corresponding state transitions governing cluster formation, maintenance, and dissolution are summarized in Table 1.

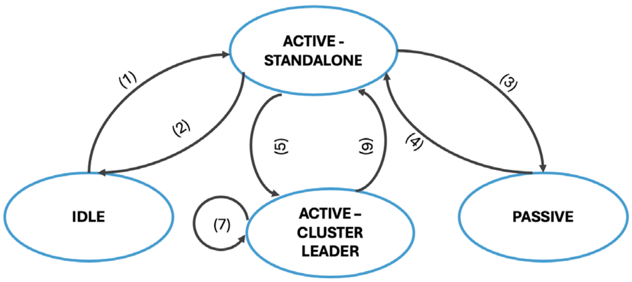

FIGURE 2. State diagram for ETSI VAM cluster operations.

TABLE 1. State transitions - ETSI VAM clustering.

Label	Description
(1)	ego starts transmitting VAMs
(2)	ego stops transmitting VAMs
(3)	the cluster has not reached its maximum number of members (e.g., 20), ego is at a certain distance away from the cluster leader (e.g., 3–5 m), and velocity of the leader is within 5% [11].
(4)	ego detects cluster leader as lost or cluster conditions are not satisfied
(5)	no cluster to join, ego has sufficient processing power, and it receives messages from 3–5 different VRUs located within 3–5 m.
(6)	ego breaks up the cluster it created (not enough power, no neighbors within a range)
(7)	shrinking/extending cluster, keep-alive messages (at least every 2 s)

IV. IMPLICIT VAM CLUSTERING

The clustering mechanism defined in the ETSI VBS relies on explicit signaling procedures to establish and maintain clusters. These procedures require additional control information exchanged between cluster members and leaders, either over the V2X channel or through auxiliary communication technologies.

In contrast, this work proposes an *implicit clustering mechanism* in which clusters emerge without negotiation between nodes. Cluster membership is inferred solely from the information already exchanged through periodic VAM broadcasts. As a result, the proposed scheme removes the need for additional signaling messages while maintaining the ability to represent groups of VRUs through a single transmitting node.

The proposed approach follows three main design principles:

TABLE 2. State transitions - implicit clustering.

Label	Description
(a)	ego starts transmitting VAMs
(b)	ego stops transmitting VAMs
(c)	ego is within cluster range from the leader (cluster conditions are met)
(d)	cluster conditions are not satisfied
(e)	no cluster to join, ego has sufficient processing power, and it receives messages from VRUs located within 5 m.
(f)	ego breaks up the cluster it created (stop offering coverage)
(g)	ego stops transmitting VAMs
(h)	leader did not send a VAM when expected plus a random jitter and ego sends a VAM offering coverage
(i)	ego receives a message from a close VRU offering coverage and yields leadership

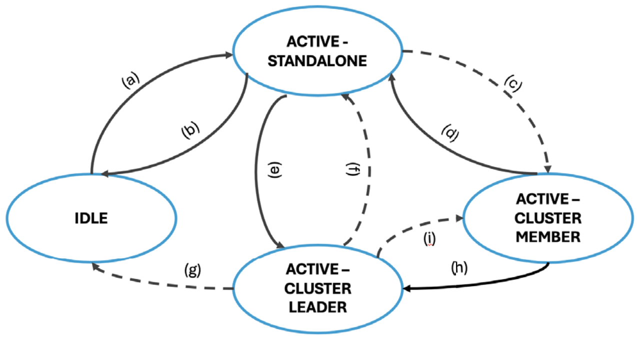

FIGURE 3. State diagram for implicit clustering.

- Cluster formation is inferred from locally observed VAMs rather than negotiated.
- No additional in-cluster communication is required beyond standard VAM transmissions.
- Cluster membership adapts naturally to mobility dynamics and communication losses.

Table 3 summarizes the signaling messages required by the ETSI clustering mechanism and contrasts them with the proposed implicit clustering scheme.

A. CLUSTER FORMATION

Each VRU periodically broadcasts VAMs according to the standard triggering conditions defined by ETSI. Nodes initially operate in *standalone mode*, where each VRU independently transmits its own VAMs.

When a node receives VAMs from neighboring VRUs located within a predefined coverage radius R_c, it evaluates whether it can act as a representative for those nodes. If this condition is satisfied, the node declares itself capable of providing cluster coverage in its subsequent VAM transmission.

Upon receiving this indication, neighboring nodes determine whether they fall within the advertised coverage region. If so, they transition to the *active cluster member* state. In this state, nodes suppress their own VAM transmissions while relying on the cluster leader to represent their presence.

TABLE 3. VAM clustering signaling messages.

Operation	ETSI Clustering	Implicit Clustering
Offer to lead	✓	✓†
Cluster Join Request*	✓‡	×
Join Success Notification**	✓‡	×
Keep alive message	✓‡	✓†
Break-up	✓‡	×†

†Uses a regular VAM transmitted at kinematic-based rate
‡Uses a new message with special containers not triggered by kinematics
* One per member
** At least one per member

TABLE 4. Simulation parameters.

Parameter	Values
Access Layer protocol	ITS-G5 (IEEE 802.11p)
Channel bandwidth	10 MHz at 5.9 GHz
Data rate	6 Mbit/s
Pedestrian transmit power	16 mW
Vehicle transmit power	20 mW
Path loss model	Two-Ray interference model
VAM generation frequency	0.2–10 Hz (ETSI VAM [11])
CAM generation frequency	1–10 Hz (ETSI CAM [16])
Max. pedestrian velocity	5 km/h
Max. vehicle velocity	60 km/h
Pedestrian density	48 ped. per 100 m segment
Vehicular density	30 veh/km per lane
Cluster shape and size	Circle of $r = 5m$

This process allows clusters to form implicitly based solely on the reception of VAMs, without requiring explicit join procedures.

B. CLUSTER MAINTENANCE

Cluster maintenance occurs passively as long as the spatial relationship between nodes remains within the coverage region defined by the cluster leader. Members continuously monitor received VAMs to determine whether the leader is still providing valid coverage.

Unlike the ETSI clustering mechanism, no additional signaling is required to maintain the cluster state. Cluster membership is continuously re-evaluated based on the reception of periodic VAMs.

The absence of explicit maintenance messages reduces communication overhead and increases robustness in lossy communication environments.

C. CLUSTER DISSOLUTION

Clusters dissolve naturally when coverage conditions are no longer satisfied. This may occur due to several factors:

- nodes moving outside the coverage radius,
- significant differences in motion dynamics between members,
- loss of VAM reception from the cluster leader.

When a node determines that it is no longer covered by a cluster leader, it automatically returns to the standalone mode and resumes its own VAM transmissions.

Because cluster break-up is implicitly determined from the reception of standard VAMs, no explicit cluster termination procedures are required.

D. IMPLEMENTATION WITHIN VAM MESSAGES

The proposed clustering mechanism does not introduce additional message types or containers. All cluster-related information is conveyed using existing VAM fields.

Consequently, the size and structure of VAMs remain unchanged, which simplifies implementation and preserves compatibility with existing ETSI-compliant communication stacks. This design also ensures that the proposed mechanism can operate under realistic communication conditions, including packet losses and intermittent connectivity.

The complete behavior of the proposed implicit clustering mechanism is described by the state machine illustrated in Fig. 3 with the corresponding state transitions summarized in Table 2. Note that even if both Figs. 2 and 3 have the same states and share most transitions, the assumptions of the Implicit algorithm are reduced since we, e.g., do not expect *join* messages within a deadline. The complexity of the algorithm is thus reduced and allows for more types of nodes to be able to *lead* a cluster.

V. PERFORMANCE EVALUATION

This section evaluates the proposed implicit clustering mechanism using network simulations. The evaluation is structured in two stages. First, the performance of the proposed scheme is compared against standalone VAM transmissions in order to quantify the benefits of clustering in terms of channel load and information freshness. Second, the proposed mechanism is compared against the clustering procedure defined in the ETSI VBS specification to assess relative performance under heterogeneous traffic conditions.

A. EVALUATION METHODOLOGY

Network performance is evaluated through simulations using the Artery framework [15], which provides a full-stack implementation of the ETSI C-ITS protocol suite, including Cooperative Awareness Messages (CAMs), VAMs, and the clustering procedures defined in the VBS specification [11]. Consequently, both the standard ETSI clustering mechanism and the proposed implicit clustering scheme are evaluated under identical communication conditions.

Simulations are performed using IEEE 802.11p (ITS-G5) operating at 5.9 GHz with a 10 MHz channel bandwidth. Table 4 summarizes the simulation parameters. Pedestrians move at a maximum speed of 5 km/h while vehicles travel up to 60 km/h. Unless otherwise stated, measurements are collected during a 60 s observation window following a 100 s warm-up period. Each scenario is repeated five times and the reported results correspond to the mean values with 95% confidence intervals.

To quantify network performance and awareness, the following metrics are used:

- **Inter-generation Gap (IGG):** the mean time interval between two consecutive VAM generations at the

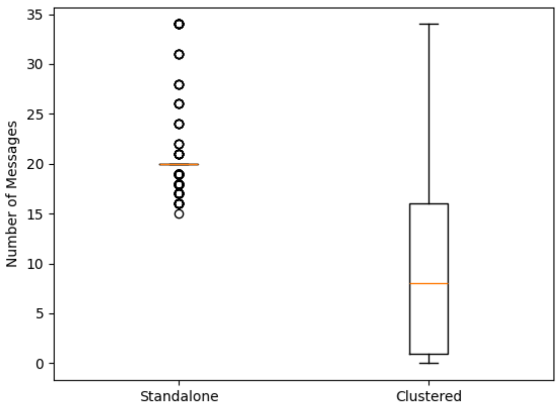

FIGURE 4. Generated VAMs per station.

transmitter.

$$\Delta t_g[i] = t_g^{VAM\rightarrow}[i+1] - t_g^{VAM\rightarrow}[i] \quad (1)$$

- **Inter-packet Gap (IPG):** the mean time interval between two successfully received VAMs from the same transmitter.

$$\Delta t_r[i] = t_r^{VAM\leftarrow}[i+1] - t_r^{VAM\leftarrow}[i] \quad (2)$$

- **VRU awareness:** the ratio between the number of VRUs successfully observed within a time window and the total number of VRUs present in the scenario [17].

$$Awareness = \frac{N\{VRU : \Delta t_r[i] < 3\,\mathrm{s}\}}{N_{tot}\{VRU\}} \quad (3)$$

A 3 s observation window was selected to ensure coverage of the maximum IGG value observed across all simulation scenarios.

B. BASELINE EVALUATION: STANDALONE VS IMPLICIT CLUSTERING

We first evaluate the effect of implicit clustering relative to standalone VAM transmissions in scenarios consisting exclusively of pedestrian traffic. Pedestrians are placed along two sidewalks on a 2 km road segment and move in both directions at a target walking speed of 5 km/h. Each pedestrian is equipped with an ITS station transmitting VAMs according to the ETSI VBS specification.

Fig. 4 shows the number of generated VAMs per station. In standalone mode, pedestrians typically generate messages at intervals of approximately 3 s, with variations caused by changes in speed and direction during interactions with other pedestrians. In contrast, implicit clustering significantly reduces message generation, as cluster members suppress their transmissions while being represented by a cluster leader. In several cases, nodes do not generate any VAM during the observation interval, as they remain continuously covered by a nearby leader.

This reduction in message generation directly affects channel load and communication reliability. Fig. 5 illustrates the relationship between IGG and IPG under increasing communication distance in the presence of vehicular traffic. In both modes of operation, the discrepancy between generation and reception intervals increases with distance due to packet losses caused by channel contention. However, by reducing the number of concurrent transmissions, implicit clustering mitigates packet collisions and maintains IPG values closer to the corresponding IGG, indicating improved delivery reliability and ensuring access to more up-to-date information.

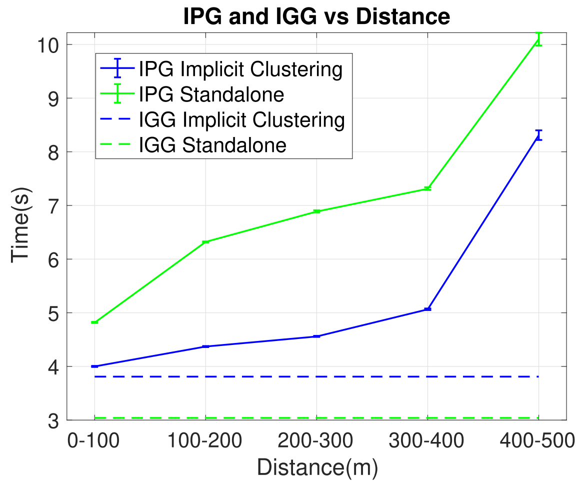

FIGURE 5. Inter-packet gaps comparison standalone vs implicit.

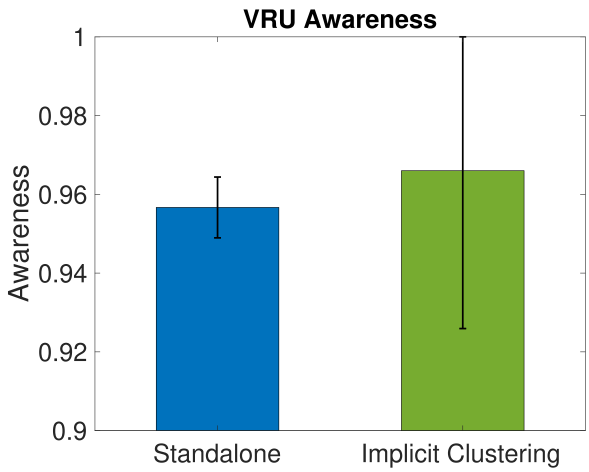

FIGURE 6. VRU awareness ratio standalone vs implicit.

The impact of clustering on network awareness is shown in Fig. 6. Although the implicit clustering scheme exhibits a slight increase in awareness variability, attributable to its reliance on cluster leaders for message dissemination, VRU awareness remains comparable to standalone operation, as indicated by the overlapping confidence intervals, even with a reduced number of transmitted messages.

These results align with the expected behavior of clustering mechanisms, in which reducing redundant transmissions can improve channel efficiency while maintaining awareness of nearby VRUs. In contrast to the ETSI approach, implicit clustering achieves this without explicit coordination overhead.

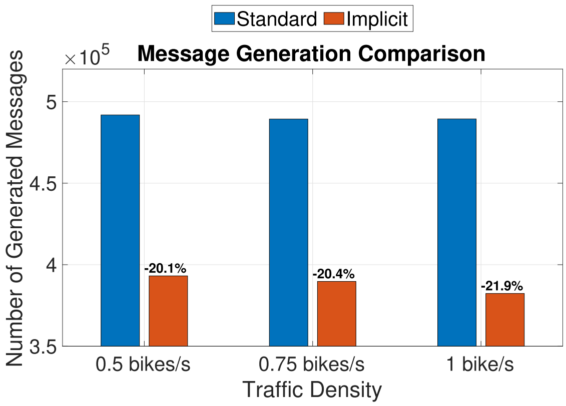

FIGURE 7. Number of generated messages standard vs implicit schemes.

C. COMPARISON WITH ETSI STANDARD CLUSTERING

The second stage of the evaluation compares the proposed implicit clustering scheme against the clustering mechanism defined in the ETSI VBS specification. To assess scalability under more dynamic traffic conditions, this scenario considers bicycle traffic interacting with vehicular traffic. Bicycles generate VAMs while vehicles periodically broadcast CAMs, contributing to the overall channel load.

The evaluation is conducted in a hybrid square-grid traffic scenario, where the left half of the network represents a suburban access area with longer, highway-like road segments, and the right half represents a denser Manhattan-style urban grid. This allows us to examine how car and bicycle traffic patterns evolve as they transition from a suburban setting into a more structured urban network.

In contrast with the previous scenario, the availability of alternative routes, together with four-way intersections and the stop-and-go effects introduced by traffic lights, lead to more frequent changes in relative position and movement behavior. Consequently, the clusters are more dynamic, as nodes regularly join and leave as proximity conditions evolve.

Three bicycle traffic densities are considered, corresponding to Poisson arrival processes with parameters $\lambda = 0.5$, 0.75, and 1.0 bikes/s. Vehicle traffic remains constant at 20 vehicles/km (equivalent to $\lambda = 0.1$ cars/s). Each experiment is repeated five times, and average values with 95% confidence intervals are reported.

Fig. 7 compares the total number of generated VAMs for the ETSI clustering mechanism and the proposed implicit clustering scheme. Across all traffic densities, implicit clustering consistently generates fewer messages than the standard approach. The relative reduction increases with traffic density, indicating that the proposed scheme scales more efficiently as the number of VRUs grows.

The impact of this reduction on communication performance is illustrated in Fig. 8. While implicit clustering exhibits a slightly higher IGG due to the lower transmission rate, it maintains IPG values comparable to those of the ETSI scheme across communication distances due to

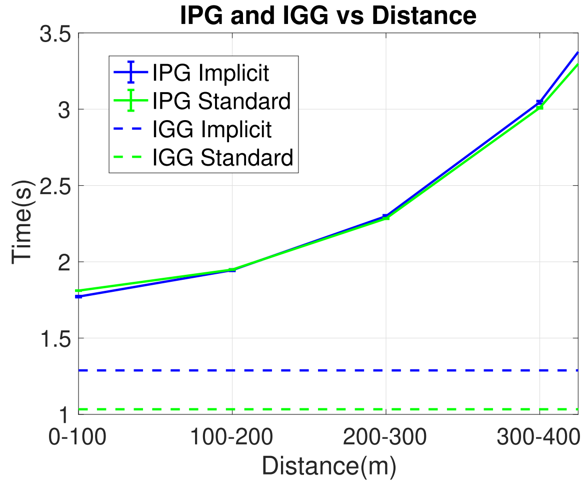

FIGURE 8. Inter-packet gaps comparison implicit vs standard.

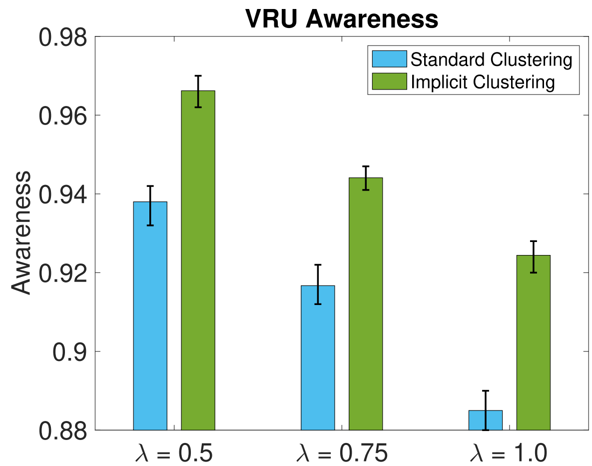

FIGURE 9. VRU awareness ratio standard vs implicit clustering.

reduced contention and packet collisions at the access layer. Consequently, the gap between IGG and IPG remains smaller, indicating that the received information more closely reflects the most recently generated state despite fewer transmissions.

Finally, Fig. 9 shows the resulting VRU awareness. Although awareness decreases for both schemes as traffic density increases, the implicit clustering approach consistently achieves higher awareness levels mainly due to reduced channel load. The non-overlapping confidence intervals across all densities indicate statistically significant improvements over the ETSI clustering mechanism.

These results highlight the scalability of the proposed approach. As traffic density increases, implicit clustering becomes increasingly effective at limiting channel load while maintaining high levels of VRU awareness.

VI. DISCUSSION

The results presented in Section V show that implicit clustering can significantly reduce the number of VAM transmissions while maintaining comparable awareness levels among road users. This is mainly due to the fact that cluster formation and maintenance emerge from the regular exchange of broadcast messages, rather than relying on explicit coordination. As a result, the proposed approach avoids the additional signaling required by the ETSI clustering scheme, reducing channel contention and improving overall communication efficiency.

A key advantage of this design is its robustness to message losses. The ETSI scheme relies on a sequence of control exchanges, including join requests, confirmations, and periodic keep-alive messages. If any of these messages are lost, cluster formation may fail or membership information may become inconsistent. In contrast, implicit clustering depends only on the reception of standard VAM broadcasts. Even when messages are occasionally lost, nodes can re-synchronize as soon as a new broadcast is received, allowing clusters to stabilize without requiring explicit recovery procedures.

This aspect is one of the main advantages of the proposed approach over standard ETSI VAM clustering. Lobo et al. [10] report that, in a clustering scenario, 37.51% of messages are triggered by the loss of a cluster leader, while 40.35% are triggered by join requests. These results align with our observations, which is expected given the similar simulation environment, namely the same toolkit with a different map. Since implicit clustering does not require explicit join requests, the latter source of messages is removed entirely. It also reduces the impact of leader loss, since nodes can either form a new cluster or return to standalone operation without explicit recovery signaling. This helps explain the reduction in generated messages observed in Fig. 7.

Furthermore, while the implicit clustering scheme reduces the number of transmissions, it does not compromise the visibility of VRUs in the network. Instead, by lowering channel load and reducing packet collisions, it helps to keep the gap between message generation (IGG) and reception intervals (IPG) smaller. This is consistent with previous results [1], which show that limiting redundant transmissions can improve the freshness of broadcast information.

Beyond reducing transmissions, implicit clustering also keeps message sizes more consistent. By avoiding cluster containers, it prevents the inclusion of additional data structures that can significantly increase packet length and introduce variability in message size, which may lead to issues at the access layer [18]. In our approach, nodes rely solely on the mandatory data elements present in every VAM to adapt their coverage implicitly, without changing the message size.

These benefits become more evident in dense VRU scenarios, where many users move in close proximity. In such conditions, redundant transmissions can quickly saturate the wireless channel and degrade reliability. By allowing groups of nearby VRUs to be represented by a single transmitting node, implicit clustering improves scalability without introducing additional coordination overhead.

Finally, some limitations should be noted. Clustering relies on spatial proximity and message reception, and can therefore be affected by positioning errors and radio propagation conditions. In addition, the current design does not account for the intended trajectory of VRUs. For instance, cyclists moving in parallel but in opposite directions may remain clustered for a short time despite having diverging paths. While this effect is more pronounced in the ETSI scheme due to its negotiated structure, it can also reduce the visibility of individual VRUs in the proposed approach. This suggests that clustering should consider motion intent, rather than relying solely on proximity.

VII. CONCLUSION

This paper presented an implicit clustering mechanism for ETSI VAMs that removes the need for explicit cluster negotiation and maintenance signaling. The proposed approach allows nodes to dynamically assume cluster leadership and provide coverage for nearby VRUs using only regular VAM transmissions.

Results show that the proposed scheme can significantly reduce message generation while maintaining VRU awareness at levels comparable to standalone operation. This behavior is consistent with the expected benefits of clustering, but is achieved here without the additional coordination overhead required by the ETSI clustering procedure. By relying solely on standard VAM broadcasts, the approach improves scalability and robustness in lossy wireless environments.

Future work will focus on extending the clustering logic to incorporate trajectory and intention information, addressing the current limitation that clustering decisions are mainly based on spatial proximity and message reception. This would allow clusters to be formed based not only on proximity but also on motion similarity. In addition, experimental validation using real-world communication platforms will be pursued to further assess the proposed mechanism under realistic operating conditions.

In this regard, it is important to consider the effect of positioning uncertainty on cluster formation, since an error even at the sub-meter level, once compounded between nodes, could trigger nodes to cluster when not necessary or to not cluster when they actually meet the requirements. These challenges, which may be visible only in real-world tests with V2X equipment, shall also be considered in future simulation work that includes positioning uncertainty with values derived from measurements in different scenarios (e.g., open air without obstructions, urban, and suburban settings).

However, even considering the inclusion of intentions and the effect of positioning uncertainty, we expect implicit clustering to surpass the performance of negotiated alternatives. Nevertheless, it is an open question on how clustering and other VRU protocols will perform in large scale implementations.

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