PassCAR: A passive clustering aided routing protocol for vehicular ad hoc networks

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A B S T R A C T

Vehicular ad hoc networks (VANETs) are a promising architecture for vehicle-to-vehicle communications in the transportation field. However, the frequent topology changes in VANETs create many challenges to data delivery because the vehicle velocity varies with time. Thus, designing an efficient routing protocol for stable and reliable communication is essential. Existing studies show that clustering is an elegant approach to efficient routing in a mobile environment. In particular, the passive clustering (PC) mechanism has been validated as a more efficient approach compared to traditional clustering mechanisms. However, the PC mechanism was primarily designed for mobile ad hoc networks (MANETs), and may be unsuitable for constructing a cluster structure in VANETs because it does not account for vehicle behavior and link quality. In this paper, we propose a passive clustering aided routing protocol, named PassCAR, to enhance routing performance in the one-way multi-lane highway scenario. The main goal of PassCAR is to determine suitable participants for constructing a stable and reliable cluster structure during the route discovery phase. Each candidate node self-determines its own priority to compete for a participant using the proposed multi-metric election strategy based on metrics such as node degree, expected transmission count, and link lifetime. Simulation results show that, compared with the original PC mechanism, PassCAR not only increases the successful probability of route discovery, but also selects more suitable nodes to participate in the created cluster structure. This well-constructed cluster structure significantly improves the packet delivery ratio and achieves a higher network throughput due to its preference for reliable, stable, and durable routing paths.

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1. Introduction

Recent advances in wireless technology have enabled mobile vehicles to form autonomous networks, called vehicular ad hoc networks (VANETs), which have become a promising architecture for delivering warning messages, disseminating traffic information, and providing Internet access. Mobile vehicular nodes in a typical VANET are equipped with wireless communication devices (e.g., on-board units), enabling inter-vehicle communication through other nodes [1–5]. A VANET can be regarded as a subset of a mobile ad hoc network (MANET). There are three main differences between VANETs and MANETs: (1) nodes in VANETs generally stay on the predefined roadway instead of moving in random directions; (2) unpredictable and inconsistent relative node velocity may cause intermittent link breakages; (3) a node in VANETs can be equipped with a global positioning system (GPS) device to easily determine its own location. These differences create significant challenges in VANET design [6,7].

As in MANETs, effective data delivery in VANETs depends on stable and reliable routing. Previous routing protocols for MANETs generally fall into two categories: table-driven and on-demand. In table-driven routing protocols [8–10], each node maintains all the information associated with the routing path, thereby consuming more storage space. In addition, frequent changes in network topology create a considerable amount of overhead for route updating. On the other hand, on-demand routing protocols such as DSR [11] and AODV [12] do not require to maintain the routing table by exploiting control messages to discover possible routes only when a node needs to communicate with another nodes. Thus, on-demand routing protocols are suitable for dynamic network environments. However, this kind of routing protocol consumes network resources and deteriorates routing efficiency because it uses the network-wide flooding technique, which introduces many control messages.

To reduce the route discovery and maintenance overhead, prior research introduces an efficient approach, called the passive clustering mechanism, that groups all nodes into multiple entities named clusters. These clusters will form a cluster structure [13–17]. Each node in the cluster structure plays either a cluster or non-cluster role, and only a subset of nodes must relay the received packet. One node in each cluster acts as clusterhead,
while the other nodes are ordinary nodes. The choice of clusterheads can be based on the value of the identifier (ID) or the degree (i.e., number of neighbors) of nodes. The typical clusterhead election approaches include the lowest-ID algorithms [13,18] and the highest-connectivity (i.e., maximum degree) algorithms [19,20]. Because a cluster structure simplifies the routing task [15], the clustering mechanism is widely used in most state-of-the-art routing protocols. However, cluster-based routing approaches suffer from serious obstacles in that each node must periodically broadcast routing information to its neighboring nodes to maintain the cluster structure, thereby causing a large number of collisions and further degrading the network throughput.

Passive clustering (PC) is an efficient clustering mechanism that passively constructs a cluster structure [21]. At any time, each node in a cluster possesses an external or internal state. When a node receives data packets, it may change its cluster state based on the state information piggybacked in on-going data packets, effectively diminishing the number of explicit control packets. The PC mechanism generates significantly less overhead for cluster maintenance than the traditional cluster-based technique because its nodes do not maintain cluster information all the time. A cluster has only one clusterhead, and multiple clusters can be connected via gateways. These two types of nodes are the main participants in message delivery. Despite their numerous advantages, previous PC-based routing protocols are only for MANETs and cannot be directly used in VANETs because they do not consider the unique characteristics of VANETs, such as node position, node velocity, and quality of wireless links. As a result, the route discovered is unlikely to be stable, reliable, or durable. These requirements pose many challenges on the design of efficient routing protocol for VANETs [22].

This paper refines the original PC mechanism and proposes a passive clustering aided mechanism, whose main goal is to construct a reliable and stable cluster structure for enhancing the routing performance in VANETs. The proposed mechanism, called PassCAR, includes the route discovery, route establishment, and data transmission phases. The main idea behind PassCAR is to select suitable nodes to become clusterheads or gateways, which then forward route request (RREQ) packets during the route discovery phase. PassCAR assesses the suitability of nodes using a multi-metric election strategy. This strategy considers link reliability, link stability, and link sustainability as the main factors and quantifies them using the metrics of node degree, expected transmission count, and link lifetime, respectively. Each clusterhead or gateway candidate self-evaluates its qualification for clusterhead or gateway based on a priority derived from a weighted combination of the proposed metrics. Once the route is discovered, the destination node replies the route reply (RREP) packet to the source node, followed by data transmission through the routing path established. This study is the first to discuss the influence of vehicle behavior and link quality on the PC mechanism. The main contribution of this study is that it designs an efficient PC-based mechanism that operates at the logical link control sub-layer, and the proposed mechanism can easily be associated with any routing protocol to support stable, reliable, and permanent data delivery. Simulation results confirm that PassCAR achieves a satisfactory path discovery ratio, network throughput, and path lifetime, as the proposed metrics can actually reflect topology changes created by variations in vehicle velocity, vehicle position, and the status of wireless links.

The rest of this paper is organized as follows. Section 2 introduces the passive clustering mechanism and addresses the challenges of PC for routing in VANETs. Section 3 presents the network model and an overview of PassCAR. Section 4 presents the proposed PassCAR in detail. Section 5 shows the performance evaluation results, while Section 6 provides concluding remarks.

2. Preliminaries

This section presents the details of the original PC mechanism and addresses the challenges of using PC for VANET routing.

2.1. The passive clustering (PC) mechanism

The passive clustering mechanism, famous for its passive behavior, can lower the control overhead in packet flooding because it uses on-going data packets instead of extra explicit control packets to construct and maintain clusters. Each node in PC can possess one of the five external states: initial (INITIAL), ordinary (ORDINARY), clusterhead (CLUSTER HEAD), gateway (GATEWAY), and distributed gateway (DISTRIBUTE GATEWAY), which represents the role of a node in the cluster structure. PC also includes two internal states, including clusterhead ready (CH READY) and gateway ready (GW READY), to represent the tentative roles of nodes. A node in any external state may enter one of the internal states upon receiving data packets, while a node in any internal state will enter one of the external states when it sends out a packet. The detailed description of the above states can be obtained in [21].

PC proposes two innovative mechanisms during cluster formation: First Declaration Wins and Gateway Selection Heuristic. The First Declaration Wins (FDW) mechanism is based on the idea of contention, in that the node first claiming to be a CLUSTER HEAD node dominates the other nodes within its communication range. The Gateway Selection Heuristic mechanism determines the minimal number of GATEWAY nodes required to maintain connectivity between clusters, thereby ensuring that a single cluster has at least two GATEWAY nodes. Note that clusterheads and gateways are the main participants in constructing the cluster structure. The PC mechanism uses a random selection strategy to determine the clusterheads and gateways, as this strategy can be effortlessly and quickly performed.

For lack of space, this study excludes the details of state transition of PC node in [21], and only gives an example of cluster structure formation of PC. Initially, all nodes are in the INITIAL state, as Fig. 1(a) shows. Suppose nodes S and D are source and destination nodes, respectively. When node S intends to transmit data to node D, it first checks its neighboring table and then enters the CLUSTER HEAD state in case of no CLUSTER HEAD neighbor, as Fig. 1(b) illustrates. Because nodes X and Y are both in the INITIAL state, they will transit to the GW READY state and enter a random waiting period for contending packet transmission, as Fig. 1(c) shows. If nodes X and Y receive no packets from the clusterhead or gateway in the same cluster, they will attempt to become GATEWAY nodes. Note that nodes X and Y are within the communication range of each other. The FDW mechanism ensures that only one node will enter the GATEWAY state. Assume that node X has a smaller backoff period than node Y. Thus, node X will become a GATEWAY node and send out the packet. Upon receiving the packet from node X, node Y will withdraw its contention and transit its state from GW READY to ORDINARY, and nodes D and Z will enter the CH READY state, as Fig. 1(d) illustrates. Then, nodes D and Z contend for being a CLUSTER HEAD node using the First Declaration Wins mechanism. Without loss of generality, assume that node D successfully becomes a CLUSTER HEAD node, and thus node Z gives up on becoming a clusterhead and reverts to the ORDINARY state, as Fig. 1(e) shows.
2.2. PC challenges in VANETs

Recall that the PC mechanism determines clusterheads and gateways using a random selection strategy. This simple strategy chooses a node with fewer neighbors or no neighbors as a clusterhead or gateway to forward RREQ packets. This creates a serious obstacle in that the next forwarding node may be undiscovered, thereby hindering the discovery of routing path. In addition, link quality is likely to be unstable in a mobile environment. If the discovered routing path includes a link with poor quality, packet transmission is likely to fail, generating more unnecessary retransmissions as a result. This significantly degrades overall network throughput. In VANETs, the connection between two vehicles is often intermittent due to vehicular movement. If the routing path consists of the link with a high probability of link breakage, it becomes less durable, thereby causing a low packet delivery ratio.

3. Network model and overview

This section presents the proposed network model, followed by an overview of the proposed PassCAR.

3.1. Network model

This paper considers the one-way multi-lane highway platoon scenario, which is a network represented by an undirected graph \( G = (V, E) \), where \( V \) is the set of nodes and \( E \subseteq V \times V \) is the set of links between two nodes. Let \( e_{ij} \in E \) denote the link between two nodes, \( n_i \) and \( n_j \). Assume that each node \( n_i \) is equipped with the GPS device so that it is aware of the geographical position. Let \( v_i \) be the velocity of node \( n_i \), and \( N_{\text{node}} \) be the number of nodes in \( n_i \)'s communication range. The node can obtain its velocity via a commercial navigation service, such as Garmin Traffic [23]. For simplicity, we assume that nodes are identical in communication range, termed \( r_c \). Assume that each node is aware of the number of nodes in its communication range via periodical advertisement (ADV) messages. Let \( s_i \) and \( cid(i) \) denote the cluster state and identifier of node \( n_i \), respectively.

3.2. Overview

PassCAR determines the number of nodes required to form a relatively stable and durable virtual backbone for data delivery in highly dynamic VANETs. The main concept of PassCAR is that a node only considers the sender’s cluster state and its current cluster state to determine whether it must change its state upon receiving RREQ packets. PassCAR can be associated with any on-demand routing protocol. This study considers the AODV routing protocol as an example to give an overview. Fig. 2 shows the format of RREQ packets, in which all fields are divided into two parts. The first part includes all the fields in the RREQ packet of the original AODV routing protocol as an example to give an overview. Fig. 2 shows the format of RREQ packets, in which all fields are divided into two parts. The first part includes all the fields in the RREQ packet of the original AODV routing protocol. The second part includes sender’s information, including sender’s position (i.e., \( x \)-coordinate and \( y \)-coordinate), velocity, cluster state, and link lifetime (LLT).

<table>
<thead>
<tr>
<th>Fields in RREQ packets of the routing protocol</th>
<th>Sender’s information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Velocity</td>
</tr>
</tbody>
</table>

Fig. 2. RREQ packet format of PassCAR.
Similar to the original PC mechanism PassCAR uses the FDW mechanism on CH\_READY and GW\_READY nodes to compete for CLUSTER\_HEAD and GATEWAY nodes, respectively. However, PassCAR exploits a novel multi-metric election strategy instead of random election approach to determine the next forwarding node to relay RREQ packets. In the proposed strategy, the CH\_READY or GW\_READY node calculates a priority, defined as the weighted combination of the proposed metrics upon receiving RREQ packets. A node with higher priority has a better chance of becoming a CLUSTER\_HEAD or GATEWAY node. A node uses its priority to determine a waiting period of time, which is inversely proportional to its priority, and then adheres to the principle of state transition of the original PC mechanism to transit its current internal state to the anticipating external state when the waiting time expires.

4. Passive clustering aided routing (PassCAR) protocol

This section explains the PassCAR design by addressing the proposed routing metrics, and also analyzes the forwarding probability of RREQ packets per hop when selecting the next forwarding node.

4.1. Routing metrics

To construct an efficient cluster structure for reliable and durable routing, PassCAR considers link reliability, link stability, and link sustainability as the primary routing factors, and uses the node degree, expected transmission count, and link lifetime as the routing metrics to represent these routing factors.

4.1.1. Node degree

Previous studies show that the node degree is a crucial factor that should be considered in cluster formation [19,20,24]. The degree of a node is the number of nodes in its communication range. Without considering node degree, the random selection approach sometimes selects a node that has no neighbors as the clusterhead or gateway. This inefficient selection may fail to construct the cluster structure or discover the routing path. To increase the successful probability of route discovery and reduce the delivery delay, PassCAR also uses the node degree as a routing metric when forwarding RREQ packets. The node degree can be measured effortlessly, in that each node periodically broadcasts ADV packets to all of its one-hop neighbors. Thus, the node degree can be derived by simply counting the number of received ADV packets from the INITIAL neighbors.

Typically, selecting a node with a smaller degree as the CLUSTER\_HEAD or GATEWAY node may create a large number of clusters. This incurs longer delivery delays and decreases channel utilization. To decrease the number of created clusters and avoid constructing a cluster structure with breakable links, PassCAR tends to select the node with the highest degree to forward RREQ packets. In case of a tie, the node with the lowest ID prevails. A CH\_READY or GW\_READY node with a higher degree should possess a higher priority.

4.1.2. Expected transmission count

The channel status of wireless links varies with time. The stability of a wireless link depends on the channel status that it uses. In PassCAR, CLUSTER\_HEAD and GATEWAY nodes are the major participants in data delivery. If these nodes are associated with unstable wireless links, data forwarding will most likely fail, requiring retransmission. Therefore, a node associated with a stable link makes a better clusterhead or gateway.

Researchers often use the expected transmission count (ETX) to measure the stability of wireless links [25,26]. ETX typically indicates the bi-directional transmission quality of a link. Let $ETX_{ij}$ denote the ETX of link $e_{ij}$. According to the definition of ETX in [25], the ETX of link $e_{ij}$ can be derived from

$$ETX_{ij} = \frac{1}{d_f \times d_r}.$$ 

where $d_f$ and $d_r$ denote the forward and reverse delivery ratios, respectively. The forward delivery ratio is the probability that a data packet successfully arrives at the recipient, and the reverse delivery ratio is the probability that the acknowledgement (ACK) packet is successfully received. In PassCAR, each node uses periodical broadcasts of ADV packets to obtain $d_f$ and $d_r$ for its neighbors, making it possible to determine the ETX.

To avoid forming an unstable link, PassCAR selects the node associated with a highly stable link to become the CLUSTER\_HEAD or GATEWAY node. A small value of ETX indicates a high-stability link. Thus, nodes associated with a smaller value of ETX should possess a higher priority.

4.1.3. Link lifetime

In highly dynamic wireless networks, it is important to reduce the probability of link breakage. In principle, sustainable links dominate the durability of routing paths. If the discovered route consists of more sustainable links, it will survive longer. As a result, the data delivery ratio increases and the overhead of route maintenance decreases. Su et al. [27] proposed a measurement, called link expiration time (LET), for selecting the routing path. Considering VANET characteristics, this study modifies the LET and introduces a metric, called link lifetime (LLT) to evaluate link sustainability. The LLT represents the duration of time two vehicles remain connected. The larger the LLT is, the more sustainable the link is. The PassCAR approach in this study is designed for a one-way multi-lane highway scenario. In a typical highway, all vehicles move in the same direction and the lane width is much smaller than the communication range of nodes. In addition, all nodes can be assumed to be synchronized using a GPS clock.

Fig. 3 shows the calculation of LLT. Suppose that nodes $n_i$ and $n_j$ are within the communication range of each other. Although node position should be represented by x-coordinate and y-coordinate, this study assumes the trajectory of all vehicular nodes is a straight line, as the lane width is small. Thus, the y-coordinate can be ignored. Denote the positions of $n_i$ and $n_j$ as $x_i$ and $x_j$, respectively. To guarantee that $n_i$ and $n_j$ are connected, the

![Fig. 3. Example of LLT calculation.](image-url)
distance between $n_i$ and $n_j$ must be less than the communication range, i.e., $-r_c \leq x_i - x_j \leq r_c$. Eq. (1) predicts the LLT of $e_{ij}$, termed $LLT_{ij}$:

$$LLT_{ij} = \frac{-\Delta v \cdot \Delta x + \Delta v \cdot r_c}{(\Delta v)^2},$$

where $\Delta v = v_i - v_j$ and $\Delta x = x_i - x_j$.

To prevent discovering an impermanent path, PassCAR selects nodes with greater LLT values to become the CLUSTER HEAD or GATEWAY node. Thus, a CLUSTER HEAD or GATEWAY node with a larger value of LLT should possess a higher priority.

4.2. Priority calculation

Recall that PassCAR identifies the participant to forward RREQ packets based on the suitability of each $CH_{READY}$ or GW_{READY} node. PassCAR uses a priority, defined as a weighted combination of node degree, ETX, and LTT, to evaluate this suitability. To guarantee that node priority is between 0 and 1, the proposed metrics must be normalized. Let $\rho_i$ be the priority of a $CH_{READY}$ or GW_{READY} node $n_i$. Let $x$, $\beta$, and $\gamma$ represent the weighted values corresponding to node degree, ETX, and LLT, respectively. $\rho_i$ can be formulated as

$$\rho_i = x \cdot \frac{N_{n_i}}{N_{\max}} + \beta \cdot \frac{1}{ETX_{ij}} + \gamma \cdot \frac{LLT_{ij}}{LLT_{\max}},$$

where $x + \beta + \gamma = 1$. The following Lemmas 1 and 2 discuss the reasonable values of $N_{\max}$ and $LLT_{\max}$.

**Lemma 1.** Given the number of lanes $n_l$ and the length of vehicular node $L$, $N_{\max} = \frac{2L}{4} \cdot n_l$. □

**Proof.** Without loss of generality, this study models the coverage area of each vehicular node as a square whose perimeter is twice the communication range (i.e., $2r_c$), as Fig. 4 shows. Let $\delta$ be the mean node spacing. The mean distance between two nodes can be represented as $L + \delta$. Let $N'$ be the mean number of nodes within the communication range. Therefore,

$$N' = \frac{2r_c}{L + \delta} \cdot n_l.$$

For simplicity, assume that the node length is constant. Apparently, node spacing decreases as the average velocity of vehicular nodes decreases. Additionally, smaller node spacing leads to fewer nodes within the communication range. Therefore, the maximum number of nodes within the communication range is derived if $\delta = 0$. Eq. (3) shows that $N_{\max} = \frac{2L}{4} \cdot n_l$. □

**Lemma 2.** Given a pre-determined positive parameter $\delta$ whose value is extremely small, we have $LLT_{\max} = \frac{2L}{\delta}$. □

**Proof.** By Eq. (1), if $\Delta v > 0$, $LLT_{ij} = -\frac{\Delta x - r_c}{\Delta v}$; otherwise, $LLT_{ij} = -\frac{\Delta x + r_c}{\Delta v}$. If $n_i$ receives the RREQ packet from $n_i$, the two nodes are within communication range, i.e., $-r_c \leq \Delta x \leq r_c$. Thus, $\frac{\Delta x - r_c}{\Delta v} \leq \frac{2L}{\delta}$ if $\Delta v > 0$, and otherwise $\frac{\Delta x + r_c}{\Delta v} \geq \frac{2L}{\delta}$. Note that a decrease in $\Delta v$ will lead to an increase in link lifetime, and $LLT_{\max}$ derives if $\Delta v = 0$. Because $\Delta v$ cannot be 0, replacing $\Delta v$ with an absolutely small positive parameter, $\delta$. That is, $-\frac{\Delta x - r_c}{\Delta v} = -\frac{\Delta x + r_c}{\delta} \leq \frac{2L}{\delta}$ for $\Delta v > 0$. On the other hand, $\frac{\Delta x - r_c}{\delta} = \frac{\Delta x + r_c}{3}$ for $\Delta v < 0$. Consequently, $LLT_{\max} = \frac{2L}{\delta}$. □

To ensure that high priority nodes become the CLUSTER HEAD or GATEWAY nodes, the multi-metric election strategy borrows the concept of random backoff from the typical carrier sense multiple access (CSMA) mechanism to defer the transmission of RREQ packets. Let $T_{w}^v$ be the waiting period of candidate node $n_v$. Thus,

$$T_{w}^v = t_{slot} \cdot I(k),$$

where $t_{slot}$ is the time slot unit, and $I(k)$ rounds the value of $k$ to the nearest integer less than or equal to $k$.

4.3. PassCAR operation

The PassCAR protocol includes three phases: route discovery, route reply, and data transmission. Initially, all nodes are in the INITIAL state. At any time, when a node intends to transmit data to a destination node, it sends the data packet to the next forwarding node if the route information exists in its routing table. Otherwise, the node initiates the route discovery phase. The node then broadcasts an RREQ packet to all of its neighboring nodes. Once a node receives the RREQ packet, it uses Algorithm 1 to determine if it must change its current state. The node then forwards the received RREQ packet if it becomes a CLUSTER HEAD or GATEWAY node. When the destination node receives the RREQ packet, it replies an RREP packet to the source node via the nodes along the discovered route. Upon receiving the RREP packet, the source node then transmits the data packet through the routing path determined.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range of values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road length</td>
<td>5 km</td>
</tr>
<tr>
<td>Number of lanes ($n_l$)</td>
<td>3</td>
</tr>
<tr>
<td>Number of vehicles</td>
<td>150, 200, 250, 300, 350</td>
</tr>
<tr>
<td>Maximum vehicle velocity</td>
<td>80 km/hr, 100 km/hr, 120 km/hr</td>
</tr>
<tr>
<td>Communication range ($r_c$)</td>
<td>250 m</td>
</tr>
<tr>
<td>Packet size</td>
<td>1000 Bytes</td>
</tr>
<tr>
<td>Traffic flow type</td>
<td>UDP</td>
</tr>
<tr>
<td>MAC protocol</td>
<td>IEEE 802.11</td>
</tr>
<tr>
<td>Channel capacity</td>
<td>1 Mbps</td>
</tr>
<tr>
<td>$t_{min}$</td>
<td>100 ms</td>
</tr>
<tr>
<td>$\delta$</td>
<td>0.000001</td>
</tr>
<tr>
<td>Routing protocol</td>
<td>AODV</td>
</tr>
<tr>
<td>Simulation time</td>
<td>100 s</td>
</tr>
</tbody>
</table>
4.4. Analysis of forwarding probability of RREQ packets

Successfully discovering the routing path is an important part of the route discovery phase. If a node fails to select the next forwarding node to forward the RREQ packet, the path cannot be discovered. The proposed node degree metric significantly dominates the success in path discovery; thus, this study analyzes the successful forwarding probabilities of RREQ packets per hop of PC and PassCAR by considering only the node degree. Let \( N_{INITIAL} \) be the actual number of INITIAL neighbors of node \( n_i \), and denote each of these neighbors by \( n_j \), where \( j = 1, 2, \ldots, N_{INITIAL} \). For simplicity, we let \( M \) be the maximum number of INITIAL neighbors of nodes. Assume that the number of INITIAL neighbors for each node follows a Poisson distribution with a Poisson-distributed random variable, \( X \), whose expected value is \( \lambda \). The probability that exactly \( k \) INITIAL neighbors will appear can be obtained by

\[
\Pr(X = k) = f(k; \lambda) = \frac{\lambda^k \cdot e^{-\lambda}}{k!}.
\]

4.4.1. Original PC mechanism

Recall that the PC mechanism uses a random approach to select the next forwarding node. That is, each \( n_i \) self-determines a backoff period of time to contend for the next forwarding node. Let the contention window size of each node be denoted as \( CW \). Because only the INITIAL neighbor can be selected as the next forwarding node, we use \( M \) as the contention window size of each node. That is, each \( n_j \) randomly selects an integer between 0 and \( M - 1 \). Considering the realistic highway platoon scenario, this study reasonably assumes that the communication range (250 m) is much larger than lane width (approximately 3.7 m). If the neighbors of each \( n_i \) receive the RREQ packets simultaneously, collision occurs and the next forwarding node will not be discovered. A collision occurs if the random numbers that all the neighbors of \( n_j \) select are identical. The probability of a collision can be derived as

\[
p_{col} = \Pr(X = N_{INITIAL}) \cdot \left( \frac{1}{M} \right)^{N_{INITIAL}} = \frac{\lambda^{N_{INITIAL}} \cdot e^{-\lambda}}{(N_{INITIAL})!} \cdot \left( \frac{1}{M} \right)^{N_{INITIAL}}.
\]
Thus, the successful forwarding probability of RREQ packets per hop can be obtained as

\[
\begin{align*}
    p_{\text{suc}} &= 1 - p_{\text{col}}^P = 1 - \sum_{i=1}^{N_{\text{IN}}} \frac{X_i^N \cdot e^{-i}}{X_i^N!} \cdot \frac{1}{M} \cdot N_{\text{IN}}^N.
\end{align*}
\]

4.4.2. PassCAR with node degree consideration

In PassCAR that only considers node degree as a routing metric, the waiting time of a candidate node depends on the number of its INITIAL neighbors. For example, node \( n_j \) fail in discovering the next forwarding node if the numbers of INITIAL neighbors of each \( n_j \), where \( j = 1, 2, \ldots, N_{\text{IN}}^N \), are identical. The probability that each \( n_j \) where \( j = 1, 2, \ldots, N_{\text{IN}}^N \) has the same number of INITIAL neighbors is obtained as

\[
\begin{align*}
    p_{\text{col}}^{\text{ND}} &= \Pr(X_1^N = 1) \cdot \Pr(X_2^N = 1) \cdots \Pr(X_i^N = 1) + \Pr(X_1^N = 2) \cdot \Pr(X_2^N = 2) \cdots \Pr(X_i^N = 2) + \cdots + \Pr(X_M^N = M) \cdot \Pr(X_2^N = M) \cdots \Pr(X_i^N = M),
\end{align*}
\]

where \( X_i \) is the random variable indicating the number of INITIAL neighbors of \( n_i \).

Assume that the numbers of INITIAL neighbors of nodes are independent. Eq. (4) then becomes

\[
\begin{align*}
    p_{\text{col}}^{\text{ND}} &= \sum_{k=1}^{M} \frac{X_k^N \cdot e^{-i}}{X_k^N!} N_{\text{IN}}^N.
\end{align*}
\]

Thus, Eq. (5) can calculate the successful forwarding probability of RREQ packets per hop.

\[
\begin{align*}
    p_{\text{suc}} &= 1 - p_{\text{col}}^{\text{ND}} = 1 - \sum_{k=1}^{M} \frac{i^k \cdot e^{-i}}{k!} N_{\text{IN}}^N.
\end{align*}
\]

5. Performance evaluations

This section describes the simulation environment, parameters, and metrics, followed by the simulation results.

5.1. Simulation setup

This study performs numerous simulations to evaluate the PassCAR performance. Use MOVE [28] and ns-2 as the mobility...
model generator and network simulator, respectively. MOVE is built on top of a micro-traffic simulator SUMO, and provides the mobility trace file containing information of realistic vehicle movements for performance evaluation using ns-2. Tab. 1 lists the simulation parameters and the range of values. The maximum vehicle velocity means that the realistic vehicle velocity is between 0 and this value. The simulation randomly selects the source and destination vehicles, and considers constant bit rate (CBR) traffic. Simulation results were averaged over 20 runs.

This paper evaluates the following main performance metrics:

- **Path discovery ratio** is the ratio of the number of RREQ packets the destination vehicle receives to the total number of RREQ packets the source vehicle sends.
- **Throughput** measures the total amount of data a vehicle transmits during the entire course of the simulation.
- **Path lifetime** means the time period during which data packets can be successfully delivered through a path.
- **Packet delivery ratio** is the ratio of total number of data packets the destination vehicle receives to the total number of data packets the source vehicle sends.

### 5.2. Simulation results

Previous research shows that the original PC mechanism outperforms numerous traditional clustering approaches in routing performance. Thus, this study only validates the effectiveness of PassCAR by comparing the PC mechanism considering the proposed metrics with the original PC mechanism. This paper further investigates the effect of weighted factors such as packet delivery ratio and network throughput on routing performance. For ease of explanation, the terms “PassCAR-degree,” “PassCAR-ETX,” and “PassCAR-LLT” denote the PassCAR mechanisms only considering node degree, ETX, and LLT, respectively.

#### 5.2.1. Path discovery ratio

The main task of routing protocols prior to data delivery is to discover a routing path. This task typically depends on high successful probability of RREQ packets per hop. That is, the higher this probability is, the higher the path discovery ratio will be. Fig. 5 compares the simulation results of successfully discovering the routing path of PC and PassCAR under a scenario in which the maximum vehicle velocity is 80 km/hr. PassCAR outperforms the original PC regardless of the number of vehicles. Results show that the “PassCAR-degree” mechanism improves the path discovery ratio by an average of 45%. This is because the “PassCAR-degree” mechanism uses the node degree as a routing metric, increasing the probability of forwarding RREQ packets per hop. Increasing this probability further achieves a higher probability of discovering the routing path. In general, increasing the number of vehicles implies that all kinds of vehicles will increase. The number of candidate forwarding vehicles will not decrease, but more collisions will generate. This tradeoff results in a approximately steady path discovery ratio as the number of vehicles increases in the original PC mechanism and PassCAR, as shown in Fig. 5.

#### 5.2.2. Number of clusters constructed

Fig. 6 shows the numbers of clusters constructed by the original PC and “PassCAR-degree” mechanisms. For both mechanisms, the number of clusters constructed remains steady even though the number of vehicles increases. However, the “PassCAR-degree” approach constructs fewer clusters than the original PC mechanism. This is because the “PassCAR-degree” mechanism considers the node degree during the route discovery phase, resulting in fewer CLUSTER HEAD and GATEWAY vehicles. Simulation results confirm that the effectiveness of node degree in discovering the routing path.

#### 5.2.3. Network throughput

Fig. 7 illustrates the average network throughput of the original PC and “PassCAR-ETX” mechanisms under scenarios with different numbers of vehicles. Recall that the link quality influences the packet successful probability of a link. Because the “PassCAR-ETX” mechanism considers ETX when forwarding RREQ packets, it is likely to select the vehicle associated with a more stable link as the next forwarding vehicle. Consequently, the “PassCAR-ETX” mechanism achieves higher throughput gain than the original PC mechanism.

![Fig. 10. Network throughput of PassCAR under different numbers of vehicles.](image)

![Fig. 11. Packet delivery ratios of PassCAR under different maximum vehicle velocities.](image)

![Fig. 12. Network throughput of PassCAR under different maximum vehicle velocities.](image)
5.2.4. Path lifetime

To discover the durable routing path, PassCAR considers LLT as a metric during the route discovery phase. Compared with the original PC mechanism, the “PassCAR-LLT” mechanism apparently constructs a route with a longer lifetime, as Fig. 8 shows. According to Fig. 8, the “PassCAR-LLT” mechanism improves path lifetime by an average of 15.8%.

5.2.5. Effect of weighted factors

In PassCAR, the candidate forwarding vehicle self-determines its priority using Eq. (2). This priority is a weighted combination of node degree, ETX, and LLT. This section explores the effect of these weighted factors. For ease of explanation, denote the values of weighted factors using a sequence in the parenthesis, and use PassCAR1, PassCAR2, and PassCAR3 to represent these three strategies. For example, “PassCAR1(0.6;0.2;0.2)” represents the PassCAR mechanism in which \( \alpha, \beta, \) and \( \gamma \) are 0.6, 0.2, and 0.2, respectively.

Figs. 9 and 10 show the packet delivery ratios and network throughput of PassCAR with different combinations of weighted values. Note that PassCAR3 prefers the node with high LLT as the next forwarding node. The routing path constructed possesses a long path lifetime. As a result, PassCAR3 has a higher packet delivery ratio than PassCAR1 and PassCAR2, as Fig. 9 shows. In addition, PassCAR3 outperforms PassCAR1 and PassCAR2 in network throughput, as the path it discovers is more durable and can achieve continuous data delivery in highly dynamic VANETs.

To investigate the influence of vehicle velocity on routing performance, this study simulates the packet delivery ratio and network throughput under scenarios with different vehicle velocities. The maximum velocities the simulation considers are 80 km/hr, 100 km/hr, and 120 km/hr, as this study focuses on the highway VANET. The packet delivery ratio typically decreases as the vehicle velocity increases, and the low packet delivery ratio implies the degradation of network throughput. Figs. 11 and 12 confirm this inference.

Figs. 11 and 12 show that PassCAR3 achieves the best performance of the three approaches. As mentioned above, PassCAR3 is more likely to construct a durable routing path. As a result, it may prolong the path lifetime and guarantee significantly higher packet delivery ratio than PassCAR1 and PassCAR2. On the other hand, PassCAR2 considering ETX as the routing metric tends to select the vehicle associated with the most reliable link to construct the routing path. Thus, this approach achieves a higher packet delivery ratio than PassCAR1 even though the vehicle velocity increases. The simulation results in Figs. 11 and 12 exhibit similar trends.

The simulation results above indicate that PassCAR3 is superior to the other mechanisms in terms of packet delivery ration and network throughput under scenarios with different numbers of vehicles or maximum vehicle velocities. This is likely because selecting the vehicle with the most durable link can guarantee that the discovered path will remain connected as long as possible.

6. Conclusions

Although the previous research confirms that the passive clustering (PC) mechanism improves routing performance in MANETs, the PC mechanism suffers from several challenges in highly dynamic VANETs. Thus, this study proposes a PC-based routing protocol, called PassCAR, to improve the routing performance of PC in VANETs. PassCAR focuses on the vehicle behavior and link quality using the routing metrics of node degree, link lifetime (LLT) and expected transmission time (ETX). This study also introduces a weighted function based on these routing metrics that allows each candidate vehicle to determine its priority to contend for the next forwarding one. Simulation results confirm that PassCAR considering only the node degree, ETX, and LLT all achieve better path discovery, network throughput, and path lifetime than the original PC mechanism. The results derived from various combinations of weighted values indicate that LLT significantly dominates the routing performance in PassCAR. On-going research on this topic is investigating the practicality of using PassCAR in urban areas. Future research should also explore the solutions to other communication types, such as multicasting and geocasting.

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References


