An Efficient Mobility-Aware Knowledge Sharing Framework for Next-Generation Internet of Vehicles

Muhammad Salah ud din, Jérôme Härri

***Abstract*—Vehicular Knowledge Networking, when integrated with *Named Data Networking (NDN)*, unfold an emerging paradigm to deliver *Knowledge*—instead of raw data to the consumer. The mechanism improves the learning process and improves the decision-making capability of autonomous vehicles. However, in constantly evolving environment, adhering to the vanilla NDN forwarding mechanism fails to retain a reliable communication path between communicating vehicles. This results in frequent path disruptions, Knowledge retransmissions, resources utilization, and intolerable delays, ultimately hindering the timely delivery of Knowledge. To address these challenges, this article envisions MAKS—an efficient *mobility-aware Knowledge sharing* framework for next-generation Internet of autonomous Vehicles. MAKS incorporates vehicular dynamics and trajectory information to develop a *Mobility-aware Forwarding Information Base (MaFIB)*, which ensures stable reverse paths and reliable Knowledge dissemination under varying network conditions. Additionally, MAKS presents efficient path recovery mechanisms that enables vehicles to carry-on Knowledge sharing in the event of potential forwarder failures, thus maintaining service continuity. Simulation results demonstrate that MAKS achieves an impressive Knowledge delivery ratio exceeding 90%, reduces path partitioning by more than 35%, and decreases the redundant retransmissions by approximately 40% compared to benchmark scheme.**

***Index Terms*—Named Data Networking, vehicular Networks, Knowledge centric networking, Internet of Things.**

I. INTRODUCTION

The rapid evolution of Internet of Things (IoT) technologies in computation, communication, and perception [1] along-with their integration to vehicular on board units has paved the way for connected and intelligent transportation systems (ITS). Equipped with a variety of sensors e.g., cameras, LiDAR, radar, and ultrasonic sensors [2], vehicles can capture critical driving/environmental conditions and share with network entities (such as neighboring vehicles, roadside units, and edge cloud stations) to improve transportation safety, traffic efficiency, and system autonomy. However, vehicular networks usually face inherent resource limitations [3], [4], making efficient resource utilization (e.g., bandwidth) essential for optimal performance. Ignoring the semantics of data and relying on indiscriminate dissemination of large volumes of data can lead to high resource utilization and congestion, potentially delaying data delivery to the consumer vehicles, which may result in catastrophic consequences.

The concept of Vehicular Knowledge Networking (VKN) [5] has emerged with the goal of transforming raw vehicular data into actionable Knowledge and enabling its sharing in the network. the term *Knowledge* in VKN refers to algorithms or machine learning models such as supervised, unsupervised, or reinforcement learning that can synthesize information into structured representations, referred as *Knowledge models* [6]. These models generate abstracted insights against the provided inputs, known as *Knowledge samples*. Knowledge sharing enable the vehicles to exchange their experiences which significantly enhances the learning process and improves decision-making capabilities. For instance, individual vehicles train traffic flow models on their locally produced data and share the trained models to develop a highly accurate and comprehensive model. The shared learning strategy reflects a swarm intelligence, which is vital for next generation ITS applications such as assisted driving and traffic control.

At present, vehicles typically utilize address-centric communication, such as the Internet Protocol (IP) [7]–[9], to enable Knowledge exchange where the consumer vehicle utilizes a unique address to locate the producer and establish an end-to-end communication path for Knowledge transfer. However, maintaining and preserving an end-to-end communication path in a constantly evolving environment is significantly challenging due to various reasons:

1) IP address assignment requires infrastructural support; however, the vehicular networks mainly operate as ad hoc or self-organizing networks that lack fixed infrastructure support [10], [11].
2) High mobility of vehicles makes it difficult to locate a specific vehicle's IP address, leading to challenges in establishing communication.
3) Address-centric communication relies on stable communication path, which is significantly challenging in a dynamic vehicular environment.

To address the aforementioned limitations, Information-Centric Networking (ICN)—and its realization, Named Data Networking (NDN)—has emerged as a promising solution [12]–[16], especially in vehicular environments. With the inherent name-based, content-centric communication philosophy, NDN effectively handles intermittent connectivity and high mobility challenges by decoupling content (i.e., Knowledge) from designated locations. However, due to rapidly evolving vehicular environment and the shared wireless medium, the traditional Interest/Data broadcast-based content retrieval mechanism in vanilla NDN may lead to a *broadcast storm*.This problem becomes worse when a consumer vehicle requests Knowledge (e.g., a roundabout) for real-time

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decision-making.

Several studies in the literature have focused on enabling real-time decision-making [5], [6], [17] by efficiently delivering the required knowledge to consumer vehicles. These approaches primarily address two aspects: (1) generating knowledge from raw data collected by vehicles, and (2) designing knowledge placement strategies to maximize its accessibility across the network. The, existing schemes predominantly rely on instantaneous metrics, such as distance or relative velocity to select optimal forwarding nodes during the knowledge acquisition process. Such metrics fail to capture inter-vehicular link stability, which is critical in highly dynamic environments where network topology changes rapidly due to mobility. Consequently, these approaches often suffer from frequent forwarding disruptions, reverse-path failures, increased knowledge losses, and redundant broadcasts.

Furthermore, existing schemes do not provide effective recovery mechanisms to handle unforeseen forwarder failures. When a forwarding node fails, current approaches typically resort to blind broadcasting or re-initiate the communication process, leading to degraded quality of service (QoS) and increased retransmissions.

Motivated by these challenges, we propose an efficient mobility-aware Knowledge sharing framework (MAKS) for vehicular Knowledge networks. MAKS extends vanilla NDN architecture by introducing a *Mobility-aware Forwarding Information Base (MaFIB)*, that leverages vehicular mobility characteristics to guide the selection of optimal next hops. This design reduces Knowledge retrieval costs and improves the Knowledge delivery rate. In addition, MAKS presents efficient Interest and Knowledge recovery mechanisms to minimize redundant transmissions during unforeseeable failure scenarios.

The core contributions of the proposed framework are as follows:

1) *MAKS* leverages Named Data Networking (NDN) as the underlying communication paradigm and proposes a state-of-the-art knowledge-sharing mechanism to ensure timely and reliable knowledge exchange among autonomous vehicles.
2) *MAKS* exploits vehicular dynamics, including speed, direction, and both current and destination trajectory coordinates, and introduces a novel naming schema to enable informed packet forwarding and reliable knowledge delivery in highly dynamic vehicular environments.
3) *MAKS* extends the baseline NDN architecture by designing a mobility-aware forwarding information base (MAFIB) to enhance the reliability of knowledge dissemination.
4) An efficient knowledge recovery mechanism is devised to mitigate knowledge loss and optimize the utilization of scarce network resources in highly dynamic vehicular networks.

Through extensive simulations using ndnSIM, we demonstrate that *MAKS* significantly outperforms benchmark scheme in terms of Knowledge delivery efficiency, reduced traffic generation, and optimized bandwidth consumption.

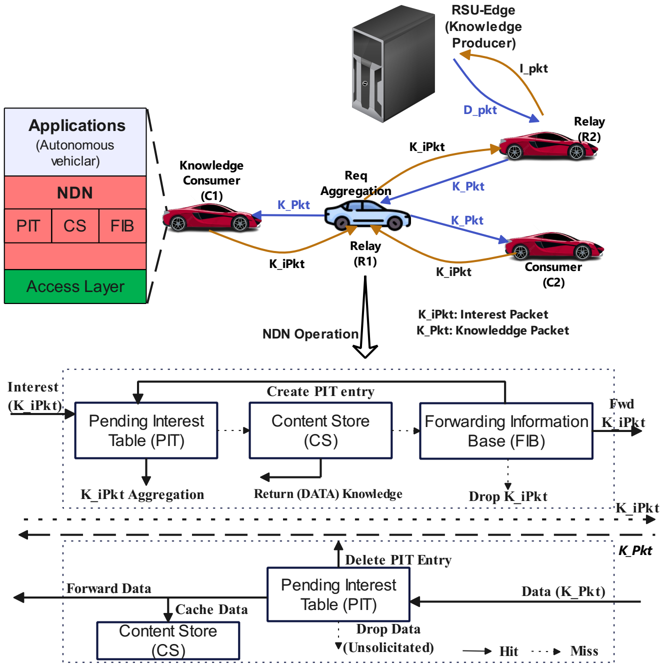


Fig. 1: NDN for Vehicular Knowledge networks.

The remainder of this paper is organized as follows. Section II provides a brief background on NDN and related work. The proposed scheme is described in Section III. The reliability and complexity analysis of the proposed scheme is presented in Section IV. Section V reports the performance evaluation and finally, Section VI concludes the paper.

II. BACKGROUND & RELATED WORK

A. Named Data Networking for vehicular Knowledge networks:

The detailed communication procedure of NDN for vehicular Knowledge networks is illustrated in Fig. 1. The process initiates when a Knowledge consumer vehicle (e.g., *C1*) forwards a request for the required Knowledge by broadcasting an Interest packet (*K_iPkt*) within its communication vicinity. Upon receiving the *K_iPkt*, each neighboring vehicle (e.g., *R1*) consults its pending interest table (*PIT*) to track outstanding Interest packets.

If a matching named entry for the received Interest packet is found, Interest aggregation is performed (as demonstrated by *R1* in the figure), preventing redundant forwarding of duplicate Interests. If no corresponding *PIT* entry exists, the vehicle proceeds to perform a content store (*CS*) lookup to check for the availability of the requested Knowledge.

If the requested Knowledge is available in the *CS*, a Data packet, i.e., *K_Pkt*, is generated and transmitted back to the consumer vehicle by following the reverse path of the *PIT* entries established along the Interest forwarding chain. Conversely, if the requested content is not found in the *CS*, the Interest packet is forwarded via forwarding information base (*FIB*) lookup to reach potential content sources.

When a Data packet is returned, it traverses the chain of *PIT* entries maintained by intermediate vehicular nodes, ensuring delivery back to the original consumer. In the event that a

Data packet arrives at a node with no matching *PIT* entry, the packet is considered unsolicited and is consequently discarded to maintain network efficiency.

B. Related work

Several efforts have been devoted to literature to improve data/Knowledge delivery in continuously changing vehicular environments [18]–[21]. Table I presents a comparison of various state-of-the-art vehicular Named Data Networks (vNDN) based schemes reported in the literature.

In [22], the authors introduced VKN and proposed an efficient Knowledge placement strategy aimed at maximizing the number of vehicles that can access the disseminated Knowledge. The approach leverages vehicular mobility patterns and computes the degree centrality of regions to determine optimal Knowledge placement locations. In [1], the authors proposed a scheme to reduce packet loss caused by frequent path disruptions due to high vehicle mobility. Their method dynamically estimates vehicle locations in real-time using parameters such as received signal strength, GPS coordinates, and speed, and forwards data packets accordingly.

In [10] authors developed the NAMECENT protocol to mitigate the broadcast storm problem in vNDN. In this work, a forwarding strategy based on name centrality and RSSI value was proposed. However, relying on name centrality values while ignoring the contact duration among vehicles may lead to path disruptions and redundant transmissions, leading to the congestion and resource over utilization. An enhanced Geographical-aware Routing Protocol (eGaRP) was proposed in [23]. eGaRP primarily focused at improving V2V communication by utilizing the directional antennas. eGaRP minimizes the redundant broadcasts during content retrieval and reduces the network resource utilization. In [24], the authors presented the routing and content transmission (RACT) protocol. RACT exploits the in-network caching and content aggregation to minimize transmission delays, reduce path failures, and enhance delivery efficiency.

Another scheme named vehicle tracking-based data packet forwarding (VTDF), was presented in [25]. VTDF addressed the link breakages between RSUs and vehicles. This work utilizes a tabu node search to track the direction of vehicle and efficiently deliver data packets.

To improve the content delivery ratio, authors in [26] proposed a density-aware delay-tolerant interest forwarding scheme for NDN-based vehicular networks. In this work, vehicle maintains neighbor information and employs a rebroadcast defer timer to reduce broadcast storms and improve efficiency. In [27] the authors proposed FoggyEdge framework. FoggyEdge integrates vehicular fog with roadside edge computing stations and leverages the microservices for in-network computations.FoggyEdge reduces computation satisfaction delays compared to the benchmark schemes.

Another NDN-based approach, CFEC [11], leverages idle computational resources of on-road vehicles to create a large-scale computing infrastructure for proximate, microservices-based tasks. CFEC introduced a zonal traffic controller that manages RSU load conditions and avoids resource over utilization through informed forwarding. Results showed that CFEC achieves reduced latency, low bandwidth usage, and decreased backhaul traffic compared to competing methods.

In [28], the authors developed CODIE to address the broadcast storm issue. CODIE introduced a hop-count field in Interest packets and a data dissemination limit (DDL) in Data packets. However, CODIE's performance deteriorates in dense scenarios, where multiple vehicles generate concurrent transmissions, leading to excessive resource consumption and performance degradation. Another scheme, LOCOS [29], extends the conventional FIB table by adding the provider's location, timestamp, and content prefix. On receiving the Interest packet, LOCOS selects the next-hop forwarder which is closer to the provider otherwise, the vanilla NDN forwarding is utilized. Several other works such as [30]–[32] stresses the challenges of latency, mobility, and reliability in distributed and vehicular networked systems , highlighting the need for efficient knowledge sharing strategies.

These schemes overlook the key vehicular characteristics e.g., trajectory information, inter-vehicular duration of contact, speed, direction, and final destination when selecting next-hop relay nodes. In addition, these schemes do not provide any recovery mechanisms to avoid path failures. Neglecting these important factors lead to increased communication delays, path breakages, and packet losses, ultimately affecting the overall QoS.

III. MAKS: PROPOSED WORK

Before delving into the operation of the proposed work, we first outline the system model and underlying assumptions. Following this, a detailed description of the MAKS framework is presented.

A. System Model and Assumptions

MAKS operates in a dynamic vehicular environment composed of multiple autonomous vehicles, each equipped with heterogeneous on-board unit (OBU) resources and exhibiting distinct mobility characteristics. Every vehicle follows an individual mobility pattern, characterized by direction, speed, and final destination.

It is assumed that each vehicle is equipped with a location estimation module (e.g., GPS) capable of providing position information in polar or cartesian coordinates, cameras, as well as speed and direction sensors. Additionally, each vehicle is assumed to possess computation, storage, and communication capabilities necessary for supporting the effective operation of *MAKS* framework.

It is worth noting that throughout this manuscript, the terms request and Interest packet are used interchangeably to refer to the NDN Interest packet, while Knowledge is used to denote the Data packet. Similarly, the terms nodes and vehicles are used interchangeably to refer to autonomous vehicles.

B. MAKS Design components

A detailed description of each building block in *MAKS* is provided as follows.

TABLE I: Related work comparison

Ref	Title	Broadcast Storm reduction	Reverse Path maintenance	Trajectory	Knowledge Recovery
[22]	VKN	×	✓	×	×
[28]	CODIE	✓	×	×	×
[33]	CDRVC	✓	✓	×	×
[10]	NAMECENT	✓	×	×	×
[23]	eGaRP	✓	✓	×	×
[29]	LOCOS	✓	✓	×	×
[34]	SCD	✓	✓	×	×
[27]	FoggyEdge	✓	✓	×	×
Proposed	MAKS	✓	✓	✓	✓

ViP Interest:

```
MAKS://vehId/vehSpeed/direction/currLoc/destLoc
```

Fig. 2: ViP Interest namespace design.

K-Interest namespace:

```
MAKS://cVehId/Rid/KnowledgeLocation(X,Y)
```

Fig. 3: K-Interest namespace design.

K-Data namespace:

```
MAKS://cVehId/Rid/KnowledgeLocation(X,Y)/
<BackupList>|Knowledge
```

Fig. 4: K-Data namespace design.

1) Naming Schema design: The naming scheme design is a crucial component of the *MAKS* framework. *MAKS* adopts hierarchical and semantically meaningful naming scheme of NDN for Interest and Knowledge namespace construction. The namespace components play a pivotal role in guiding request forwarding and ensuring reliable Knowledge delivery.

- *Vehicle information proliferation namespace design:* The vehicle information proliferation (ViP) naming scheme plays a pivotal role in maintaining information about neighboring vehicles.It enable consumer vehicles to select the most appropriate neighboring vehicle as the next-hop relay, facilitating reliable request and Knowledge delivery with a minimal number of transmissions across the network. As illustrated in Fig. 2, the ViP namespace consists of the following components:
  a. **vehId** – A unique identifier assigned to each vehicle.
  b. **vehSpeed** – The current speed of the vehicle.
  c. **direction** – The moving direction of the vehicle.
  d. **currentLoc/destLoc** – The geographical coordinates of the vehicle's current position and its intended destination.
- *Knowledge Interest (K-Interest) namespace design:* A consumer requiring Knowledge of a specific region/location generates and transmit a K-Interest packet. The K-Interest namespace, presented in Fig. 3, composed of the following components:
  a. **Consumer Vehicle ID (cVehId)** – A unique identifier for the vehicle initiating the Knowledge request.
  b. **Potential Relay ID (Rid)** – The unique identifier of the vehicle considered as a potential relay.
  c. **Knowledge Location (X, Y)** – The geographical location of the requested Knowledge.
- *Knowledge Data (K-Data) namespace design:* The K-Data namespace shown in Fig. 4, which represents the data (i.e., Knowledge) response against the K-Interest packet, includes the following components:
  a. **Consumer Vehicle ID (cVehId)** – A unique identifier of the consumer vehicle.
  b. **Potential Relay ID (Rid)** – The unique identifier of the potential relay.
  c. **Knowledge Location (X,Y)** – represents the required Knowledge location i.e., location for which the Knowledge is required.
  d. **<Backup List>** – A list of backup nodes designated to continue forwarding the data in the event of potential forwarder failure. The backup list is derived from the MaFIB, where nodes are organized based on DoC. A subset of the top-k candidates is selected to form the backup list.
  e. **Knowledge** – The requested Knowledge.

2) Mobility aware forwarding information base (MaFIB): Before delving into the detailed description of the proposed *mobility aware forwarding information base (MaFIB)*, we first highlight the structure of the conventional NDN *FIB* and discuss its compatibility issues within dynamic autonomous vehicular networks.

The *FIB* maintains a list of name prefixes and their associated outgoing interfaces. These interfaces are used to forward name-based requests that do not find a match in the *PIT*. When an Interest packet is forwarded, the node records the corresponding outgoing interface in the *PIT*. This process continues until the Interest reaches the producer. Upon receiving the Interest, the producer generates the corresponding Data packet and forwards it back to the consumer by following the breadcrumb trail of *PIT* entries established along the reverse path.

The conventional NDN forwarding is developed for communication in stable environments, where routers equipped with multiple interfaces deliver the consumer's request toward the producer and reliably deliver the corresponding Data packet back to the consumer. However, in vehicular environments, communication occurs over adhoc interfaces, and vehicles

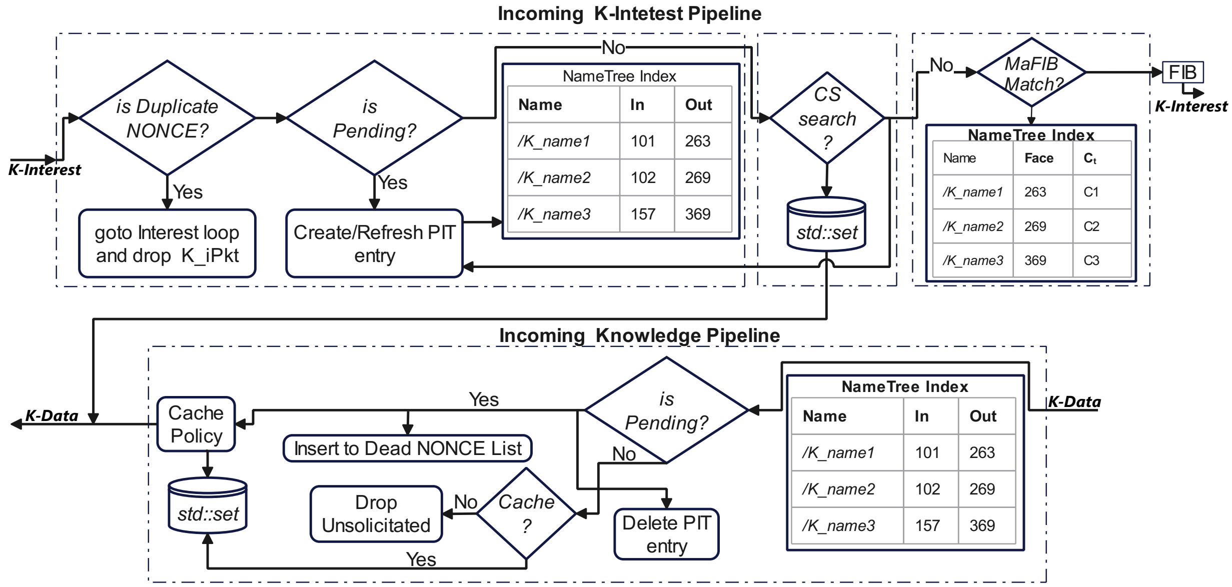


Fig. 5: MaFIB-based relay selection.

frequently change their positions. A vehicle may be connected to another at one moment and disconnected the next. Therefore, following the conventional NDN, maintaining a reliable communication path and achieving optimal interface selection becomes challenging in such dynamic conditions.

To address these challenges, *MAKS* introduces *MaFIB*—a mobility-aware *FIB* design based on vehicular dynamics. MaFIB aims to ensure the reliable Knowledge delivery in highly dynamic vehicular environments. The complete procedure for *MaFIB*-based forwarder selection is illustrated in Fig. 5, while a detailed *MaFIB* development procedure is provided as follows.

The *MaFIB* development initiates during the network initialization phase, where a vehicle located at a specific road segment transmits a *ViP Interest* packet within its communication radius. This packet notifies the neighboring vehicles of its presence and mobility characteristics, such as speed, direction, current location, and destination coordinates. A vehicle may receive multiple *ViP Interest* packets from neighboring vehicles, each with varying characteristics. Importantly, each neighbor may exhibit a different *Duration of Connectivity (DoC)* with the receiving vehicle.

A vehicle positioned closer to the Knowledge producer or consumer but with a short connection time may not serve as an optimal relay. The rationale is that it may quickly move out of the consumer's communication range, resulting in potential connectivity losses. Therefore, the *DoC* plays a crucial role in ensuring:

1) Reliable forwarding of *K-Interest* packets,
2) Stability of the reverse path during *K-Data* transmission, and
3) Reduced redundant *K-Data* packet transmissions and efficient bandwidth utilization.

Consider a mobile vehicle (f_p), located at a certain position (x_{fp}, y_{fp}), moving with velocity (v_{fp}) in direction (θ_{fp}). f_p receives a *ViP* packet from a neighboring vehicle f_l, which is located at position (x_{fl}, y_{fl}), moving with velocity (v_{fl}) in direction (θ_{fl}).

Since the vehicles are moving in specific directions within a two-dimensional plane, the distance between f_p and f_l can be computed as follows:

$$d_{fp\leftrightarrow fl} = \begin{bmatrix} (r_{fp}\cos\theta_{fp} - r_{fl}\cos\theta_{fl})^2 + \\ (r_{fp}\sin\theta_{fp} - r_{fl}\sin\theta_{fl})^2 \end{bmatrix}^{\frac{1}{2}} \tag{1}$$

Expanding and simplifying the Eq.1

$$d_{fp\leftrightarrow fl} = \begin{bmatrix} {r_{fp}}^2(\cos^2\theta_{fp} + \sin^2\theta_{fp}) \\ + {r_{fl}}^2(\cos^2\theta_{fl} + \sin^2\theta_{fl}) \\ - 2r_{fp}r_{fl}(\cos\theta_{fp}\cos\theta_{fl} \\ + \sin\theta_{fp}\sin\theta_{fl}) \end{bmatrix}^{\frac{1}{2}} \tag{2}$$

Since $\cos^2\theta + \sin^2\theta = 1$, and $(\cos\theta_{fp}\cos\theta_{fl} + \sin\theta_{fp}\sin\theta_{fl}) = \cos(\theta_{fp} - \theta_{fl})$, by incorporating these values and simplifying Eq.2, we get $d_{fp\leftrightarrow fl}$ as shown in Eq.3

$$d_{fp\leftrightarrow fl} = \left[{r_{fp}}^2 + {r_{fl}}^2 - 2r_{fp}r_{fl}\cos(\theta_{fp} - \theta_{fl})\right]^{\frac{1}{2}} \tag{3}$$

The proposed scheme follows the same procedure to compute the distance between f_p and the final destination of f_l, denoted as $d_{f_p\leftrightarrow \text{dest}_{f_l}}$. This distance allows f_p to determine the overlapping portion of its journey with f_l on the way to the destination.

Given that the vehicles are moving in the same direction, the velocity difference between f_p and f_l (i.e., Δ_v) can be computed as shown in Eq.4.

$$\Delta_v = |v_{fp} - v_{fl}| \tag{4}$$

Case 1: If f_l is moving ahead of f_p, then f_l leaves the vicinity of f_p earlier as it has already covered some distance. Therefore, DoC denoted as C_t can be computed as follows:

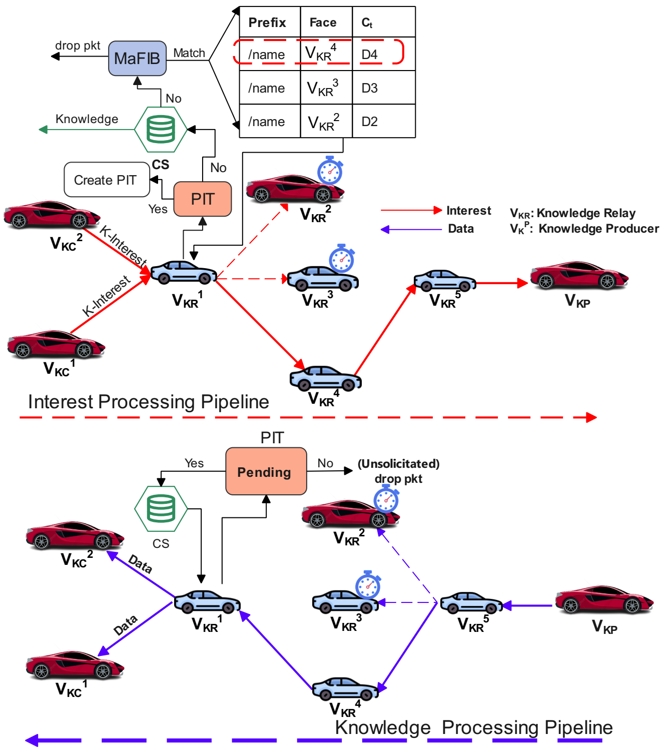


Fig. 6: Standard K-Interest and K-Data forwarding under stable network conditions

$$C_t = \frac{d_{fp\leftrightarrow dest_{fl}} - d_{fp\leftrightarrow fl}}{\Delta_v} \tag{5}$$

Case 2: If f_p is moving ahead of f_l, then f_p leaves the vicinity of f_l earlier as it has already covered some distance. Therefore, C_t can be computed as follows:

$$C_t = \frac{d_{fp\leftrightarrow dest_{fl}}}{\Delta_v} \tag{6}$$

To forward a *K-Interest* packet, f_p selects the next-hop relay that has the highest C_t value with respect to itself.

It is important to note that the *MaFIB* is updated in two cases:

1) Upon expiration of C_t values.
2) Upon reception of a *ViP* packet.

The reason is that a neighboring vehicle is considered to have left the communication range of f_p once its C_t value expires. Offloading to such vehicles may lead to unacceptable delays, potential packet losses, and unnecessary bandwidth consumption. Additionally, *ViP* packets ensures that *MaFIB* remains up to date, enabling consumer vehicles to take informed forwarding.

C. MAKS: Resilient K-Interest and K-Data Pipelines with Automated Recovery

Considering the highly varying environment, where autonomous vehicles frequently alter their positions, frequent path breakages may occur. These disruptions may lead to *K-Interest* and *K-Data* packet losses, increased retransmissions, and delayed Knowledge delivery.

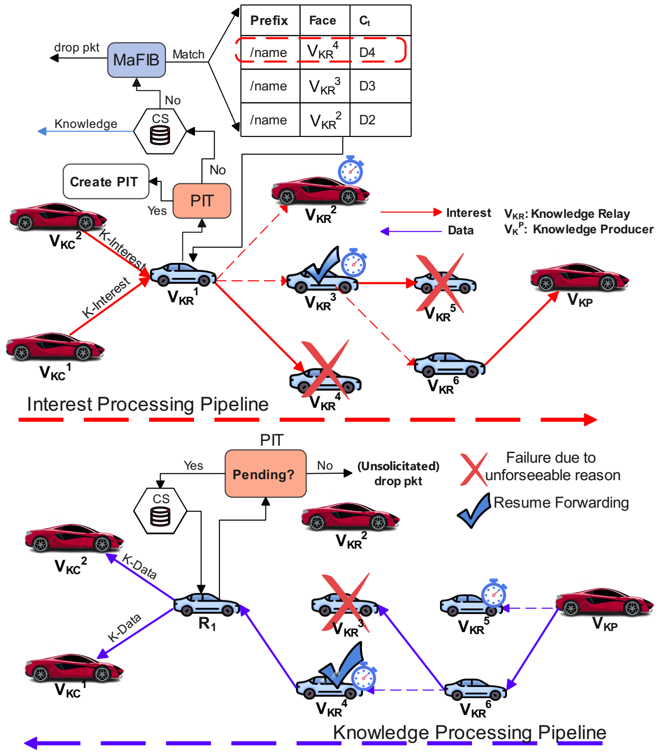


Fig. 7: K-Interest and K-Data forwarding with recovery under Path failure conditions

To address these challenges, *MAKS* introduces efficient *K-Interest* and *K-Data* processing pipelines with automated recovery mechanisms. Algorithm 1, and Algorithm 2 presents the complete MAKS request initiation to Knowledge delivery procedure while detailed description is presented as follows.

Upstream K-Interest Packet Pipeline: The consumer vehicle, e.g., V_{KC}^{1}, requiring Knowledge about a location (e.g., a roundabout, highway, or T-section), identifies a suitable relay node V_{KR}^{1}—the one having the maximum C_t with V_{KC}^{1}—by consulting its locally established *MaFIB*. The selected relay V_{KR}^{1}, along with its immediate neighbors, receives the *K-Interest* packet. Instead of discarding the packet as unsolicited, the immediate neighbors attach a timer and temporarily buffer the *K-Interest* packet in anticipation of potential recovery forwarding.

The *K-Interest* reaches the producer via two forwarding modes:

1) **Standard K-Interest Forwarding under Stable Network Conditions:**
The standard *K-Interest* forwarding under stable network conditions can be visualized in the upper half of Fig. 6. In this case, V_{KR}^{1}, upon receiving the *K-Interest*, first verifies the authenticity of the packet. It then checks its *PIT* to determine if a request for the same *K-Interest* has already been transmitted. If a matching entry is found, request aggregation is performed. Otherwise, V_{KR}^{1} consults its local CS. If the Knowledge is not found in the CS, V_{KR}^{1} consults its *MaFIB*, identifies the next-hop relay node with the highest C_t heading towards the V_{KP}, and

forwards the *K-Interest* packet. Immediate neighbors (if any) of V_{KR}^{1} overhear the forwarding, stop their timer, and discard the *K-Interest*. This process continues until the *K-Interest* packet reaches the producer.

2) **K-Interest Forwarding with Recovery under Path Failure Conditions:**
The *K-Interest* forwarding with recovery under path failure conditions is depicted in the upper half of Fig. 7. In this mode, if the initially selected relay node fails to forward the *K-Interest* toward the Knowledge Producer, its immediate neighbors—those oriented in the direction of the producer—take over and continue forwarding the Interest packet until it reaches the destination.
The complete procedure, shown in the upper portion of Fig. 7, proceeds as follows: Knowledge consumers (e.g., V_{KC}^{1} and V_{KC}^{2}) forward the Interest packet to the designated relay node V_{KR}^{1}. Upon receiving and verifying the Interest, V_{KR}^{1} consults its *MaFIB* and forwards the packet to V_{KR}^{4}. During this transmission, neighboring nodes V_{KR}^{2} and V_{KR}^{3} also receive the Interest.
V_{KR}^{2} and V_{KR}^{3} temporarily cache the Interest and associate it with a forwarding timer, remaining on standby while V_{KR}^{4} is expected to continue the forwarding process. However, as shown in the figure, V_{KR}^{4} encounters a failure and is unable to proceed. V_{KR}^{3} (whose timer expires first among the remaining candidates) resumes the forwarding process. This opportunistic recovery mechanism continues until the Interest packet reaches the Knowledge Producer, V_{KP}.

Downstream K-Data Packet Pipeline:

1) **Standard K-Data Forwarding under Stable Network Conditions:**
The standard *K-Data* forwarding under stable network conditions is presented in the lower half of Fig. 6. On receiving a *K-Interest* packet from a downstream vehicle, the producer node, i.e., V_{KP}, verifies the packet and generates the corresponding *K-Data* packet. It then appends a list of backup downstream potential forwarders to the packet and forwards it toward V_{KC}^{1} via the designated forwarder in the breadcrumb path. The purpose of appending a list of backup forwarders is to ensure continuity in *K-Data* forwarding in the event of a failure of the designated forwarder—such failures may result from high mobility, *OBU* failure, or other unforeseen disruptions.
When the designated downstream forwarder receives the *K-Data* packet, it verifies the packet's authenticity and forwards it to the next lower-layer forwarder en route to the consumer. Meanwhile, backup nodes initiate a forwarder timer upon receiving the *K-Data* packet and temporarily cache the packet. If the designated forwarder successfully relay the packet, the backup nodes cancel their timers and clear their cache entries to prevent cache pollution.

2) **K-Data Forwarding with Recovery under Path Failure Conditions:**
V_{KP} generates a *K-Data* packet and forwards it to

Algorithm 1 : MaFIB development and maintenance

```
sender Id ← $vehId$
function RecieveViPInterest()
    Search $vehId$ in $MaFIB$;
    Extract the vehicular dynamics;
    compute $C_t$ using Eq.1 to Eq.6
    if $MaFIB$ not empty && $vehId$ in $MaFIB$ then
        Update corresponding $MaFIB$ entry;
    else
        Create new $MaFIB$ entry;
    end if
end function
```

Algorithm 2 : MAKS Knowledge sharing

```
Input: Knowledge_Interest ← $K_I$
Output: Knowledge_Data ← $K_D$
function Forward_Interest()
    Select $K_R$ From MaFIB
    Forward Interest toward $K_R$
end function
function Recieve_Interest()
    if (nodeId == $K_R$) && (CS does not contain $K_D$) then
        Forward Upstream;
        Create a PIT entry;
    else
        Attach timer with $K_I$ and wait
        if (timer == 0)  then
            Forward Upstream;
            create a PIT entry;
        end if
    end if
    if (nodeId == $K_R$) && nodeId == $K_P$) then
        Generate $K_D$;
        Append backupList with $K_D$;
        Forward Knowledge ;
    end if
end function
function Recieve_Data()
    if (nodeId == $K_C$)  then
        Knowledge Received;
    end if
    if (nodeId == $K_R$) && nodeId ≠ $K_C$) then
        Forward downstream;
    else if (nodeId in backupList) then
        Associate timer with $K_D$ and wait
        if (timer == 0)  then
            Continue Forwarding Downstream;
        end if
    else
        Unsolicited Data packet
        Drop
    end if
end function
```

the appropriate vehicle along the breadcrumb path. A *Knowledge Data recovery mechanism* is triggered if any vehicle in the breadcrumb path fails to forward the *K-Data* packet toward the consumers (V^1_{KC} and V^2_{KC}). To mitigate packet loss, avoid the random broadcasting of large data packets, and enable path recovery, the V_{KP} selects and appends a list of potential downstream (backup) nodes to the data packet before forwarding it along the breadcrumb path.

On receiving, each backup node temporarily caches it and associates a timer with the cached copy. If the designated downstream node fails, the backup node whose timer expires first takes over and resumes the forwarding process. This mechanism continues until the *K-Data* packet reaches to the consumer.

As illustrated in the lower half of Fig. 7, the V_{KP} generates a *K-Data* packet, appends backup nodes' list, and forwards it toward V^6_{KR} in the reverse path. Upon verifying the received packet, V^6_{KR} updates the backup node list by adding V^4_{KR} as a new forwarding candidate and then offload the packet to V^3_{KR}. Being a backup node, V^4_{KR} also receives the *K-Data* packet, caches it temporarily, and sets an associated timer. If V^3_{KR} unable to continue forwarding due to any unforeseeable reason, V^4_{KR} takes over and forward the packet toward V^1_{KC} and V^2_{KC}.

Finally, on receiving the *K-Data* packet, V^1_{KR} compares received packet name with the pending entries in its *PIT*. If PIT hit successful, V^1_{KR} immediately forwards packet to V^1_{KC} and V^2_{KC}.

IV. RELIABILITY AND COMPLEXITY ANALYSIS

A. Reliability Analysis

The reliability analysis is crucial to ensure the consistent delivery of K_D in distributed Knowledge-centric networks. The algorithm leverages PIT entries, timers, and backup node lists to mitigate uncertainties such as node failures, data unavailability, and unsolicited packet drops. The core reliability factors are analyzed as follows.

1) Interest Handling Robustness: The `Receive_Interest()` function ensures that interest packets are processed exclusively by the selected K_R. If the requested Knowledge is not available in the CS, the interest packet is forwarded toward upstream nodes, and a corresponding PIT entry is created. Each interest is associated with a timer that enables retransmissions in the event of failures. This mechanism enhances overall fault tolerance.

2) Redundancy via Backup Lists: When K_P generates a Knowledge packet, it appends a *backupList* of candidate nodes to the packet. This strategy ensures that, in the event of a failure along the breadcrumb path, a potential intermediate node from the backup list can continue forwarding the packet, thereby improving successful delivery rates. Such redundancy substantially enhances end-to-end path reliability, particularly in dynamic and lossy vehicular environments.

3) Handling Unsolicited Data: The proposed algorithm validates incoming data packets and discards them if they are identified as unsolicited, thereby preventing the propagation of potentially stale or malicious information. This mechanism ensures that only requested content traverses the network, avoiding unnecessary resource utilization and reducing congestion.

B. Complexity Analysis

The complexity analysis of MAKS algorithm (i.e., Algorithm 2) is presented as follows.

1) Time Complexity:

- **Forward_Interest():** The operation includes Knowledge relay K_R selection from the MaFIB. The best case selection is $O(1)$ and $O(n)$ for the worst case, where n denotes the number of entries in MaFIB.
- **Receive_Interest():** ReceiveInterest() function performs a condition check, PIT entry creation, and potential retries using timers.

$$T_{ReceiveInterest} = O(1) \tag{7}$$

- **Receive_Data():** In Receive_Data() function, Data forwarding mainly depends on whether the node is K_C, in the backupList, or an unsolicited receiver. Each case composed of relevant checks and forwarding:

$$T_{ReceiveData} = O(1) + O(b) \text{ where } b = |\text{backupList}| \tag{8}$$

2) Space Complexity:

- **PIT Table:** Each PIT entry stores an interest and a timeout value. For m interests:

$$S_{PIT} = O(m) \tag{9}$$

- **Backup List:** The backup list stores K_D instances temporarily. Assuming d data instances:

$$S_{BackupList} = O(d) \tag{10}$$

- **MaFIB Table:** Static memory for routing entries:

$$S_{MaFIB} = O(n) \tag{11}$$

3) Overall Complexity: The overall runtime for a single interest-data exchange in MAKS is:

$$T_{MAKS} = O(1) + O(1) + O(b) \tag{12}$$

Where b is typically small, bounded by network fanout. Thus, MAKS exhibits low computational overhead suitable for real-time and resource-constrained environments.

V. EVALUATION

This section deals with the software-based simulation studies accompanied by detailed simulation parameters, performance evaluation metrics, and evaluation results.

The comprehensive description is provided as follows.

TABLE II: Simulation parameters

Parameter	Value
Simulator	NS-3 (ndnSIM)
Communication stack	NDN
Mobility generator	SUMO
Number of Knowledge consumers	4
Number of Knowledge Producers	4
Wireless interface	IEEE 802.11p
Network size (i.e., number of vehicles)	50-60
Vehicle Transmission Range	175m
Average vehicle speed	10m/s, 25m/s
Knowledge request rate	5-10 requests/sec
Simulation time	200s

A. Simulation Setup

To analyze the performance of the proposed MAKS framework, extensive simulations were conducted using ndnSIM, an ns-3-based NDN simulator.The simulations were conducted on a system equipped with an Intel Core i7 processor and 16 GB of RAM. To construct a realistic urban vehicular environment, SUMO (Simulation of Urban Mobility) [35] was integrated with ndnSIM as the mobility generator. The scenario models an urban mobility environment comprising T-shaped intersections, where vehicles approach and leave the intersection, resulting in dynamic topology changes.

The performance of MAKS was evaluated against a state-of-the-art baseline, the Enhanced Geographical-aware Routing Protocol using directional antennas for NDN-VANETs (eGaRP), using several key performance metrics: Knowledge Delivery Ratio, Request Satisfaction Delay, Route Disruption Ratio, Number of Retransmissions, and Bandwidth Consumption.

The network size was varied from 15 to 60 nodes, with vehicle speeds ranging from 10 m/s to 25 m/s. The IEEE 802.11p standard was employed as the underlying MAC/PHY layer protocol, with a communication range of 175 meters.

The complete simulation parameters can be visualized in in Table II.

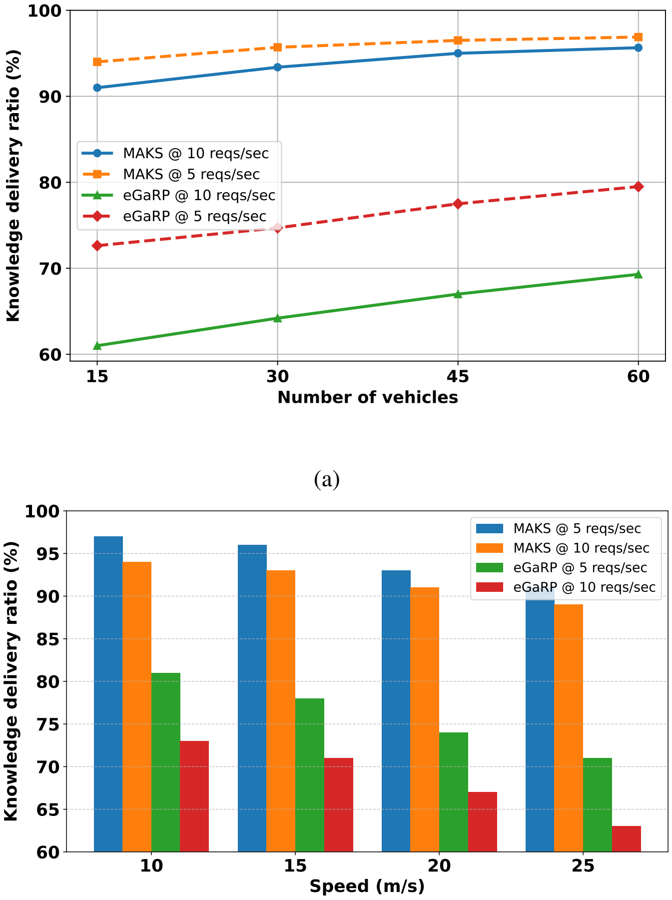
To evaluate the performance of MAKS against the benchmark schemes the following metrics are considered:

1) **Knowledge delivery ratio (KDR):** KDR is defined as the ratio of Interest packets that successfully retrieve the corresponding Knowledge.
Mathematically, KDR is expressed as:

$$KDR = \left[\frac{\sum_{1}^{n} I_{\text{hit}}}{\sum_{1}^{n} I_{\text{hit}} + \sum_{1}^{n} I_{\text{miss}}} \right] \times 100 \tag{13}$$

where I_{hit} denotes the Interest packet that successfully received the requested Knowledge, and I_{miss} denotes Interest packet that failed to do so.

2) **Request satisfaction delay (RSD):** RSD is the total time elapsed from when a request is sent by the consumer to when the corresponding Knowledge is received. It includes the request transmission time, processing time at the producer, and the response delivery time.



(a)

(b)

Fig. 8: Knowledge Delivery Ratio

3) **Path disruption ratio (PDR):** PDR refers to the proportion of instances in which the end-to-end communication path between the consumer and the producer is disrupted or partitioned during the Knowledge acquisition process.

$$\text{PDR} = \frac{N_{\text{disrupted}}}{N_{\text{total}}} \times 100 \tag{14}$$

4) **Number of Knowledge retransmissions:** This metric represents the total number of retransmissions triggered for Knowledge packets that were lost or not acKnowledged during the initial transmission.

$$\text{KR} = \sum_{i=1}^{n} R^{(i)} \tag{15}$$

5) **Bandwidth utilization:** Bandwidth utilization denotes the total amount of bandwidth utilized for acquiring Knowledge, including all transmissions and retransmissions over the network.

B. Evaluation Results

1) Knowledge Delivery Ratio (KDR): The timely Knowledge delivery is crucial for consumer vehicles to make prompt

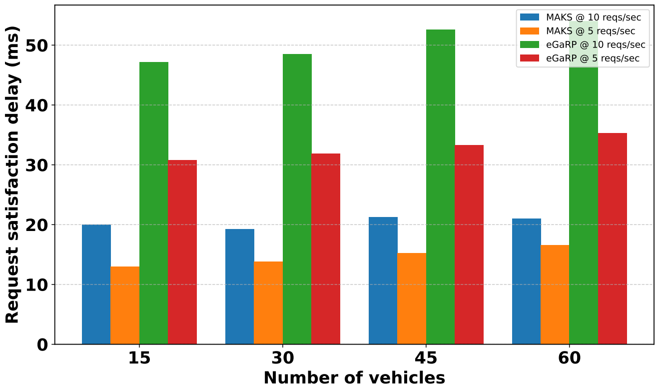


Fig. 9: Request satisfaction delay versus number of vehicles

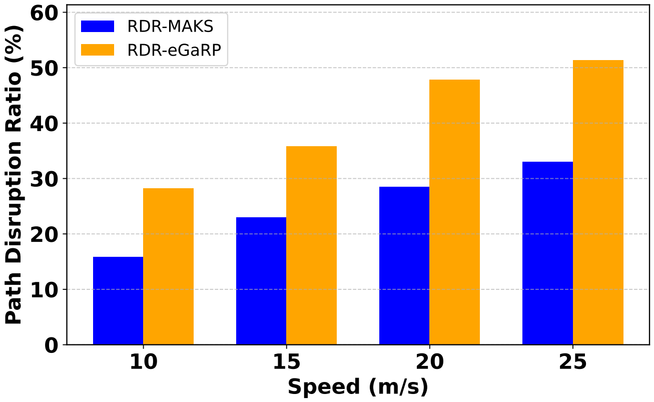
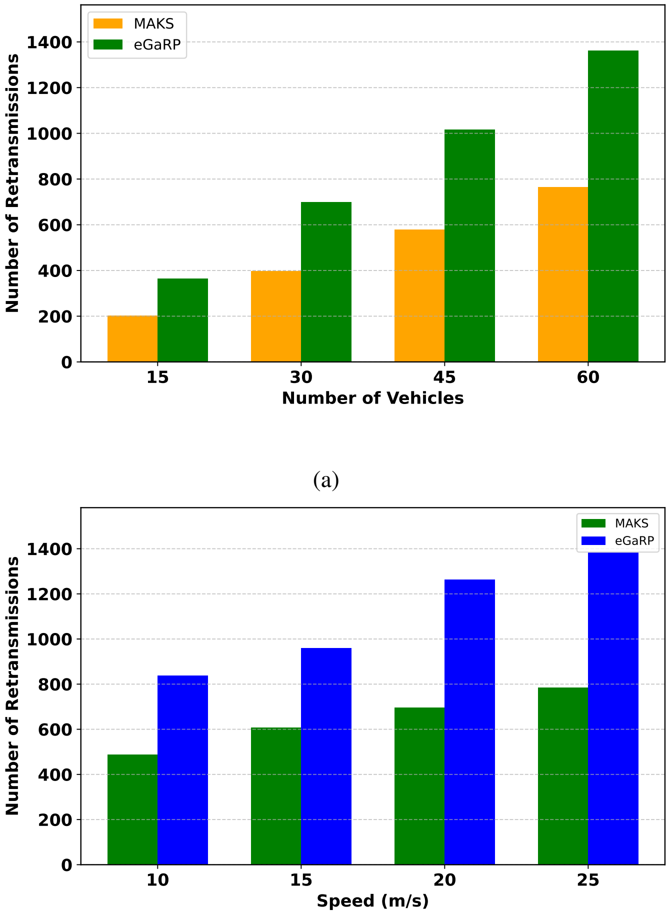


Fig. 10: Path disruption ratio versus speed

decisions, thereby ensuring road safety and enhancing passenger comfort. To analyze the effectiveness of the MAKS against the eGaRP scheme, we evaluated the KDR under varying network conditions. Specifically, we varied the number of vehicles and their speeds, while also considering two interest packet rates: 5 requests/sec and 10 requests/sec.As shown in Fig. 8(a) and Fig. 8(b) respectively, MAKS significantly outperforms eGaRP across all scenarios. In both interest rates, MAKS achieves an impressive KDR exceeding 90%, even as the network becomes more dynamic due large number of vehicles or higher speeds. This improvement stems from the *MaFIB-enabled forwarding*, which intelligently selects the optimal next-hop forwarder based on the maximum DoC. Such informed selection reduces the chances of reverse path disruption and ensures reliable Knowledge delivery to the consumer.

Additionally, the MAKS employs robust *upstream and downstream recovery mechanism*, which enables neighboring vehicles to locally repair broken paths caused by high mobility. The mechanism plays a important role in maintaining high KDR even under highly dynamic conditions.

In contrast, eGaRP lacks mobility-aware mechanisms and does not support recovery from reverse path failures which results in frequent disruptions in Knowledge delivery and a lower overall KDR. The absence of fault tolerance and recovery strategies in eGaRP further exacerbates the performance degradation in mobile environments.



(a)

(b)

Fig. 11: Number of Knowledge retransmission

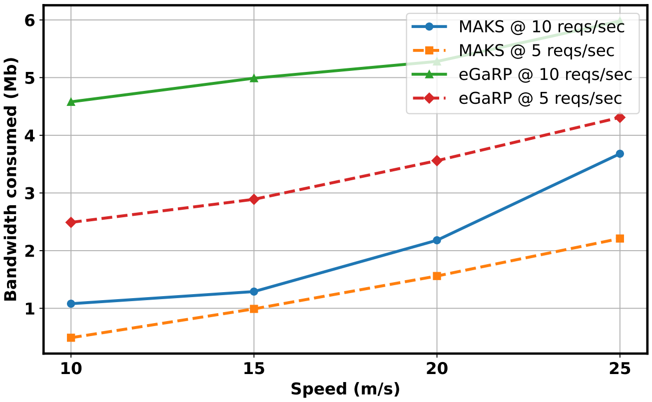


Fig. 12: Bandwidth consumption versus speed

2) Request Satisfaction Delays (RSD): RSD of MAKS and eGaRP, as a function of the number of vehicles and varying interest generation rates (i.e., 5 and 10 requests/sec), is illustrated in Fig. 9. The results shows that in all network densities and request rates, MAKS achieves low RSD compared to the benchmark scheme. This performance gain is attributed to core design features of MAKS. Firstly, the MaFIB-enabled controlled forwarding, combined with resilient K-Interest and K-Data pipelines, highly reduces packet drop rates and mitigates network congestion. The automated recovery mechanisms effectively handle the failures without excessive retransmissions. Secondly, the incorporation of a backup list in Knowledge delivery phase minimizes redundant transmission of large knowledge packets, further reducing latency.

Conversely, the benchmark scheme mainly relies on directional antennas and node location information for data forwarding. However, retaining accurate position and ensuring stable communication is challenging in dynamic vehicular environments. Such limitation leads to frequent path disruptions and network congestion, which collectively result in higher RSD values.

3) Path disruption ratio (PDR): Fig. 10 illustrates the PDR as a function of varying vehicular speed. As shown in the figure, the PDR increases with vehicle speed in both schemes, indicating the impact of high mobility on link stability. However, MAKS achieves significantly lower PDR compared with eGaRP. This performance improvement is attributed to MaFIB enabled selective relay procedure, which prioritizes relays based on high DoC to the consumer. The mechanism reduces the likelihood of path failures. Additionally, MAKS integrates path recovery mechanisms assisted by backup nodes, which ensure rapid rerouting and continuity in Knowledge dissemination.

In contrast, eGaRP relies on geographic-based forwarding via breadcrumb paths, which becomes less reliable in mobile environments due to the difficulty of maintaining up-to-date positional data. This leads to frequent path disruptions and increased PDR.

4) Number of Knowledge retransmission: The number of Knowledge retransmissions under varying vehicle densities and mobility speeds is illustrated in Fig.11(a) and Fig.11(b), respectively. The results shows that MAKS significantly reduces the number of Knowledge retransmissions compared to the eGaRP. This reduction is primarily achieved through MAKS's robust upstream and downstream Knowledge recovery mechanisms. Specifically, MAKS leverages neighboring vehicles as backup relays—both for Interest forwarding (upstream) and Data forwarding (downstream)—allowing for speedy recovery and continuation of the Knowledge transfer process if a designated forwarder fail or becomes unavailable. This proactive relay selection helps prevent redundant broadcasts and mitigates retransmissions.

In contrast, eGaRP depends on breadcrumb-based geographic forwarding. The approach suffers from frequent reverse path disruptions, as it lacks the ability to adapt to real-time vehicular mobility. Furthermore, the absence of mobility-aware characteristics in eGaRP's forwarding strategy exacerbates path breakages, resulting in excessive retransmissions and elevated communication overhead.

5) Bandwidth utilization: The bandwidth utilization of the proposed MAKS compared with the benchmark eGaRP scheme is presented in Fig. 12. To analyze the bandwidth utilization, vehicular speed was varied with increments of 5 m/s. The results clearly show that MAKS consistently outperforms eGaRP across all speed conditions and request rates. In both schemes bandwidth utilization increases with increase in speed due to frequent path disruptions and the resulting retransmissions. However, MAKS demonstrates lower bandwidth consumption. For instance, at 25 m/s with 10 req/s, MAKS utilize 3.8 Mb compared with the eGaRP's 5.5 Mb, achieving a 31% reduction. Similarly, at 25 m/s with 5 req/s, MAKS consume 2.3 Mb against eGaRP's 4.3 Mb, reflecting a 46% saving. On average, MAKS minimizes bandwidth utilization approximately 43% against eGaRP in all scenarios. The rationale is MAKS's efficient upstream and downstream path recovery mechanisms, which enables neighboring vehicles to resume communication during potential relay failure. By doin so (i.e., mitigating path losses and redundant retransmissions), MAKS effectively minimizes the overall bandwidth utilization.

In contrast, eGaRP do not provide any recovery strategies, resulting in frequent retransmissions and substantially higher bandwidth utilization.

VI. CONCLUSION

This paper presents MAKS, an efficient knowledge-sharing framework designed to provide timely knowledge delivery to consumer vehicles in highly dynamic vehicular environments. An efficient mobility-aware knowledge forwarding mechanism assisted by MaFIB is devised to enable guided forwarding and enhance reliability under frequent topology changes. Moreover, novel upstream and downstream knowledge recovery mechanisms are developed to maintain communication in the presence of path disruptions, thereby minimizing redundant transmissions, optimizing network resource utilization, and improving overall network QoS.

Simulation results demonstrate that MAKS achieves average Knowledge Delivery Ratio overall 90%, reduces request satisfaction delay by more than 55%, mitigates path disruption over 35%, decreases the redundant retransmissions by approximately 40%, and lowers bandwidth utilization by nearly half compared to benchmark scheme.

As part of future work, we plan to develop a testbed using robotic vehicles equipped with Raspberry Pi devices to evaluate the real-world performance of the proposed framework. In parallel, we aim to integrate MAKS in an decentralized agentic AI framework for next generation IoV, where autonomous agents can collaboratively reason, share knowledge, and adapt decisions across vehicles and network infrastructure.

VII. ACKNOWLEDGEMENTS

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