Towards Mobility Aware Knowledge Sharing in Vehicular Knowledge Networks

Muhammad Salah ud din, Jérôme Härri
EURECOM, 450 route des Chappes
06904 Sophia-Antipolis, France
{Muhammad.Salah-Ud-Din, jerome.haerri}@eurecom.fr

***Abstract*—Modern artificial intelligence (AI) techniques, combined with powerful far-edge computing capabilities, enable vehicles to cooperate, generate, and share knowledge with other vehicles over ad-hoc wireless technologies. In such decentralized vehicular knowledge networks, Named Data Networking (NDN) offers a promising paradigm to link knowledge consumers and producers without reliance on centralized infrastructure. One challenge in sharing knowledge over NDN lies in its redundancy-based multi-hop dissemination mechanism, which can introduce inefficiencies and delays. Given the size and time sensitivity of knowledge, this necessitates fast and reliable dissemination strategies. This paper presents Mobility-Aware Knowledge Sharing (MAKS), a scheme that considers vehicular dynamics and trajectory information to develop a mobility-aware forwarding information base (MaFIB), ensuring reliable knowledge sharing and reverse path stability in continuously varying network conditions. Simulation results show that MAKS achieves a knowledge delivery ratio above 90%, reduces the path partition rate by over 40%, and lowers the number of retransmissions by more than threefold compared to other approaches.**

I. Introduction

The technological advancement in IoTs' computational, communication, and perceptual capabilities and their integration with the vehicular onboard unit (OBU) has brought a slew of compute-intensive and delay-sensitive vehicular applications. Considering modern autonomous vehicular applications (e.g., assisted driving, coordinated platooning, smart routing, and safety driving) and the dynamic vehicular environment, the conventional sense-and-blind transmission mechanisms may no longer be sufficient. The rationale is that neglecting the semantics of data and relying on blind data dissemination may lead to increased network resource utilization and congestion, potentially preventing consumer vehicular applications from receiving the requested data on time, which may result in catastrophic situation.

To address these challenges, Vehicular knowledge networking (VKN) [1] was introduced with the precise aim of transforming the generated data into knowledge and sharing the knowledge among the network entities with associated lifetime and relevance. The term knowledge in VKN refer to the algorithms or Machine learning models (e.g., Supervised, unsupervised, Reinforcement learning) capable of synthesizing information into structured knowledge known as "knowledge models". These knowledge models are applied to get abstracted information against the provided input referred to as the "knowledge samples".

Several efforts have been devoted to literature about knowledge definitions, efficient placement and storage in autonomous vehicular environment [1]–[3]. However, how to efficiently share the knowledge among the producer and consumer considering the highly varying vehicular environment is still need to be investigated. The existing studies [2], [3] select the relay vehicle based on its relative speed or distance to the producer to forward the request (Interest) or knowledge (Data). However, maintaining a stable end to end connectivity in continuously evolving environment by utilizing aforementioned metrics may never be possible resulting in communication stragglers and long latencies. Moreover, conventional vehicular communications usually follows the inefficient address-based TCP/IP protocol, which further increases delays as a result of congestion in dense traffic scenarios.

To address the limitations of the traditional TCP/IP model and enable efficient content sharing, *Information-Centric Networking* (ICN)—particularly its prominent realization, *Named Data Networking* (NDN)—has emerged as a promising paradigm, especially for vehicular environments. NDN shifts the conventional address-centric communication model of IP networks to a *content-centric* model, allowing consumers to retrieve data directly by its name rather than its physical location. This name-based architecture enables more resilient and efficient communication by decoupling content from specific sources, thereby effectively managing challenges such as *intermittent connectivity* and *high mobility* common in vehicular networks. Furthermore, NDN's *data-centric communication model*, with its inherent *in-network caching* and *content-level security*, aligns well with the requirements of future vehicular networks, making it a strong candidate for next-generation vehicular communication standards and architectures.

Apart from its inherent benefits, vanilla NDN employs a limited broadcast strategy and maintains breadcrumb paths for data retrieval. However, establishing and preserving a stable end-to-end path in highly dynamic vehicular environments is particularly challenging, often leading to increased data retrieval costs and frequent path failures. To address these limitations, this paper introduces mobility-aware knowledge sharing (MAKS) in vehicular knowledge networks, aimed at preventing communication failures caused by path disruptions. MAKS modifies the vanilla NDN protocol by developing an efficient mobility-aware forwarding information base (MaFIB) based on the inter-vehicular duration of contact (DoC). The

TABLE I
RELATED WORK COMPARISON

Ref	Title	Broadcast Storm reduction	Reverse Path maintenance	Trajectory	Knowledge Recovery
[2]	VKN	×	✓	×	×
[4]	CODIE	✓	✓	×	×
[5]	CDRVC	✓	✓	×	×
[6]	NAMECENT	✓	×	×	×
[7]	eGaRP	✓	✓	×	×
Proposed	MAKS	✓	✓	✓	✓

DoC formulation leverages vehicular dynamics such as trajectory information, speed, and vehicle direction. In addition, we designed upstream Knowledge interest recovery and downstream knowledge data Recovery mechanisms to mitigate communication losses in the event of unforeseen failures. The core contributions MAKS are summarized as follows:

1) MAKS presents a unique knowledge-sharing framework, utilizing NDN as the underlying communication architecture, to enable efficient knowledge delivery with optimized resource utilization.
2) MAKS extends vanilla NDN by developing a mobility-aware FIB (MaFIB) to ensure reliable knowledge sharing in highly dynamic vehicular environments.
3) We developed novel upstream and downstream knowledge interest and knowledge data recovery mechanisms to minimize knowledge losses and reduce network congestion by avoiding redundant broadcasts.

The remainder of this paper is organized as follows: Section II provides related work. The proposed MAKS algorithm is presented in Section III. Section IV is devoted to the performance evaluation and finally, Section V concludes the paper.

II. RELATED WORK

Several efforts have been made to improve data delivery in vehicular NDN [8]. Table I presents a comparison of various state-of-the-art NDN-based schemes devoted to the literature.

In [2], the authors introduced Vehicular Knowledge Networks (VKN) and devised an efficient knowledge placement strategy aimed at maximizing the number of vehicles that can access the knowledge. The work utilized vehicular mobility and computed the degree centrality of regions to determine optimal knowledge placement locations. In [9], the authors developed a scheme to reduce packet losses caused by frequent path disruptions due to high vehicle mobility. Their approach dynamically estimated vehicle locations in real-time by leveraging parameters such as received signal strength (RSS), GPS coordinates, and speed, and then forwarded data packets accordingly.

The NameCent [6] was developed to address the issue of broadcast storms in Vehicular Named Data Networks (VNDN). NameCent proposed a forwarding strategy based on name centrality and received signal strength indicator (RSSI). However, relying on persistent centrality values without considering the contact time between vehicles can result in redundant broadcasts, leading to network congestion and over-utilization of resources. An enhanced Geographical-aware Routing Protocol (eGaRP) was proposed in [7], primarily targeting the improvement of V2V communication using directional antennas. eGaRP reduces message broadcasts during the data retrieval process and optimizes network resource usage. To enhance the packet delivery ratio, the authors in [10] proposed a Density-Aware Delay-Tolerant interest forwarding scheme for NDN-based vehicular networks. In this work, each vehicle maintains information about its neighbors, and a rebroadcast defer timer is used to mitigate the broadcast storm in the network. In [4], authors developed CODIE aimed to tackle the broadcast storm problem. CODIE introduced a hop-count field in Interest packets and a Data Dissemination Limit (DDL) in Data packets. However, CODIE's performance may degrade in dense networks, where multiple nodes participate in Interest and Data transmissions, leading to resource over-utilization and quality-of-service (QoS) degradation. Another scheme, named LOCOS [11], incorporates the provider's location, timestamp, and content prefix into the FIB table and selects the next-hop forwarder that is closer to the provider's location.

The aforementioned state-of-the-art schemes do not take into account key vehicular characteristics such as trajectory information, inter-vehicular contact duration, and speed when selecting the next-hop relay node. Moreover these work do not consider the significant size of *Knowledge* compared to data, i.e. NDN vs. VKN. Neglecting these factors can result in communication delays, path breakages, and packet losses, ultimately leading to degraded quality of service (QoS).

III. MAKS ALGORITHM

A. System Model and Assumptions

MAKS considers a dynamic vehicular environment composed of multiple autonomous vehicles equipped with heterogeneous OBU resources. It is assumed that each vehicle is outfitted with a location module (e.g., GPS for location estimation using polar or Cartesian coordinates), speed sensors, and direction sensors, in addition to computation, storage, and communication units. Each vehicle shares its speed, trajectory, and position information with neighboring vehicles, enabling informed and efficient knowledge sharing.

It is important to note that throughout this manuscript, the terms "nodes" and "vehicles" are used interchangeably to refer to autonomous vehicles. Additionally, the term "Knowledge Interest" refers to the Interest packet, while both "Knowledge Data Packet" and "Knowledge" refer to the Data packet.

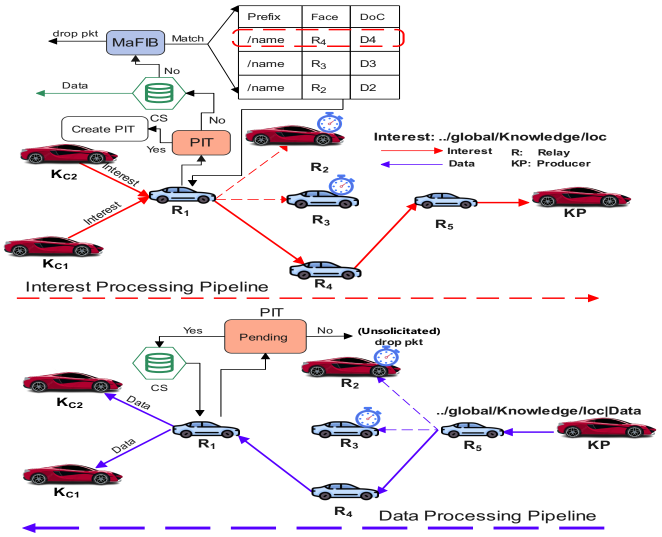

Fig. 1. Normal mode MaFIB enabled interest and Knowledge forwarding.

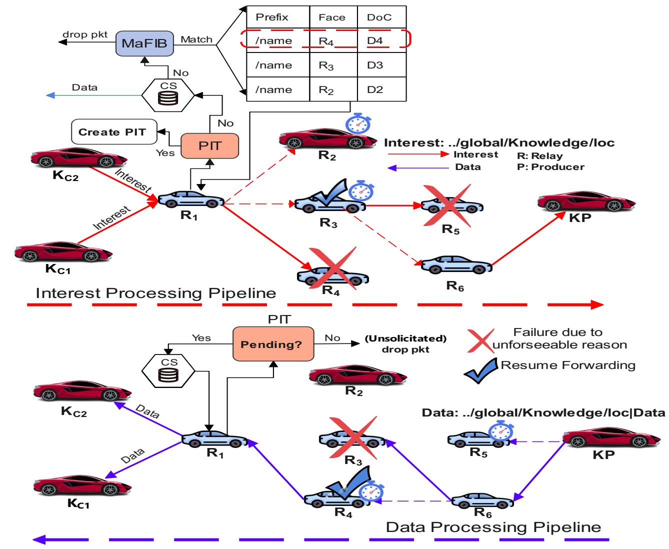

Fig. 2. Recovery mode MaFIB enabled interest and Knowledge forwarding.

B. Mobility aware Forwarding Information Base (MaFIB):

A consumer vehicle may have several neighboring vehicles with varying dynamics, such as speed, direction, and destination. Each neighbor may experience a different DoC with the consumer vehicle. A vehicle in close proximity to the knowledge producer, yet possessing a short connection time with the consumer and/or producer, may not serve as an ideal forwarding candidate, as it could quickly move out of their communication range, resulting in potential knowledge loss. Given that vehicles in vehicular networks frequently change their positions based on speed and direction, a vehicle might be connected with another vehicle at one moment but disconnected at another. Therefore, a vehicle's DoC plays a pivotal role in ensuring: 1) reliable Interest/Data forwarding, 2) reverse-path stability during data transfer, and 3) reduction of redundant bits transmissions and bandwidth utilization.

The development of *MaFIB* initiates when vehicles share information such as speed, direction, and trajectory data (e.g., current and destination location coordinates) with their neighbors. Consider a vehicle (f_p) with position coordinates (x_{fp}, y_{fp}) moving at a certain velocity (v_{fp}) and direction (θ_{fp}) receives an Interest packet from a neighboring vehicle f_l comprising position (x_{fl}, y_{fl}), velocity(v_{fl}), and direction (θ_{fl}). The distance between f_p and f_l can be computed as follows.

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

Since the vehicles are moving in the same direction, the velocity difference between f_p and f_l can be computed as follows.

$$v_{fp\leftrightarrow fl} = |v_{fp} - v_{fl}| \qquad (2)$$

Based on the above equation, we can compute the DoC as follows.

1) If f_l is moving ahead of f_p, the f_l leaves the vicinity of f_p earlier as it has already covered some distance, therefore, DoC can be computed as follows.

$$DoC = \frac{d_{fp\leftrightarrow dest_{fl}} - d_{fp\leftrightarrow fl}}{v_{fp\leftrightarrow fl}} \qquad (3)$$

2) If f_p is moving ahead of f_l, the f_p leaves the vicinity of f_l earlier as it has already covered some distance, therefore, DoC can be computed as follows.

$$DoC = \frac{d_{fp\leftrightarrow dest_{fl}}}{v_{fp\leftrightarrow fl}} \qquad (4)$$

Where $v_{fp\leftrightarrow fl}$ is the velocity difference between f_l and f_p.

The f_p organizes the *MaFIB* entries in decreasing order based on the DoC. It selects the next-hop relay with the highest DoC as shown in Fig. 1, and this process continues until the Interest reaches the Knowledge producer. It is worth noting that f_p reorganizes the *MaFIB* entries whenever a new neighbor joins the network. Additionally, when the DoC expires, the corresponding entries are deleted.

C. MaFIB enabled Knowledge sharing and Recovery Procedure:

The potential relay vehicle may fail to forward the Knowledge Interest or Knowledge Data packet due to unforeseen reasons such as internal faults, sudden route changes, etc., resulting in communication delays, packet losses, and network congestion. To mitigate this, MAKS introduced recovery mechanisms for both the Interests and knowledge-sharing phases. Algorithm 1 presents the complete MAKS Knowledge sharing procedure while detailed description is presented as follows.

1) Upstream Knowledge Interest Recovery: In the Knowledge Interest Recovery mode, if the selected relay node (from the *MaFIB*) fails to transmit the Knowledge Interest toward the Knowledge producer, the immediate neighbors of the relay, heading in the direction of the producer, continue forwarding the Interest until it reaches the consumer. The complete procedure is depicted in the upper half of Fig. 2 and is explained as follows.

As illustrated in the upper half of Fig. 2, knowledge consumers (i.e., $K_{C1}$and K_{C2}) forward the Interest packet toward relay R_1. Upon receiving and verifying the Interest, R_1 consults the *MaFIB* and forwards the Interest to R_4, which is also received by neighboring nodes R_3 and R_2 due to shared medium. Both R_3 and R_2 temporarily cache the Interest, associate a forwarder timer with the received Interest packet, and wait for R_4 to continue the Interest packet transmission. However, as shown in the figure, R_4 fails to transmit further due to an unforeseen issue. As a result, R_3, whose timer expires first, takes over the transmission. This process continues until the Interest reaches the Knowledge producer (K_P).

2) Downstream Knowledge Data Recovery: Knowledge Data packets are usually orders of magnitude larger than Interest packets. Considering the resource-constrained and continuously varying vehicular environment, blindly forwarding knowledge while ignoring the stable reverse path may lead to frequent packet losses and network congestion, resulting in delayed delivery and compromised quality of service (QoS). To prevent unnecessary Knowledge broadcasts, avoid Knowledge losses, and ensure a stable reverse path, MAKS introduces an efficient Knowledge Data Recovery procedure (as shown in Fig. 2). A detailed description is provided below.

The knowledge producer (i.e., K_P) generate a Data packet and forward it to the potential vehicle in the breadcrumb path. The Knowledge Data recovery mechanism is triggered when a potential vehicle in the breadcrumb path fails to continue forwarding the Knowledge Data packet toward K_{C1} and K_{C2}. To prevent packet loss and the random broadcast of large Data packets, as well as to recover the broken path, K_P selects and appends a list of potential downstream nodes (backup nodes) to the Data packet and forwards it along the reverse path. Upon receiving the packet, these backup nodes temporarily cache it and associate a timer with it. If the designated downstream node fails, the backup node with the earliest timer expiration takes over and continues forwarding the packet. This process continuous until the packet reaches the consumer.

As shown in the scenario presented in the lower half of Fig. 2, the K_P generates a Knowledge Data packet, appends a list of backup nodes, and forwards it along the reverse path towards R_6. Upon verifying the received Knowledge packet, R_6 updates the list of backup nodes (by adding R_4 as a potential backup node) and then forwards the packet to R_3. As a potential backup node, R_4 also receives the Knowledge packet, temporarily stores it, and associates a timer with the cached Data packet. Upon failure of R_3, R_4 forwards the Data packet in the direction of consumers. Upon receiving Data packet, the R_1 compare the name of received Data with their outgoing requests record in the PIT immediately forwards the Data packet towards K_{C1} And K_{C2}. It is worth noticing here that, the immediate neighboring vehicles purge their cache upon the transmission of interest/Data to avoid cache pollution. Moreover, the timer is computed based on the DoC, if DoC is high the waiting timer will be low. The mechanism allows the more stable vehicle to take part in the communication process to avoid the communication stragglers due to path partition.

Algorithm 1 : MAKS Knowledge sharing

Input: Knowledge Interest $\leftarrow K_I$
Output: Knowledge Data $\leftarrow K_D$
function FORWARDINTEREST()
    Select K_R From MaFIB
    Forward Interest toward K_R
end function
function RECIEVEINTEREST()
    if (nodeId == K_R) && nodeId $\neq K_P$) **then**
        Forward Upstream;
    else
        Associate timer with K_I and wait
        if (timer == 0) **then**
            Forward Upstream;
        end if
    end if
    if (nodeId == K_R) && nodeId == K_P) **then**
        Generate K_D;
        Append backupList with K_D;
        Breadcrumb Forwarding;
    end if
end function
function RECIEVEDATA()
    if (nodeId == K_C) **then**
        Knowledge Received;
    end if
    if (nodeId == K_R) && nodeId $\neq K_C$) **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

IV. PERFORMANCE EVALUATION

We evaluated the effectiveness and benefits of MAKS via python-based simulations. We developed a scenario modeling a realistic vehicular traffic environment, where vehicles are positioned according to a Poisson Point Process (PPP). Each vehicular node independently requests or responds with knowledge. The vehicles follow a highway mobility model, traveling in the same direction at varying speeds toward their respective destinations. The DoC between vehicles varies based on

TABLE II
SIMULATION PARAMETERS

Parameter	Value
Simulations	Python
Number of vehicles	50
Transmission Range	250m
Road segment	2000m
Speed	10, 35 m/s
Simulation time	200s

their relative speed and overlapping journeys. We compared the proposed work with state-of-the-art approaches, including NameCent: Name Centrality-Based Data Broadcast Mitigation in Vehicular Named Data Networks [6], and A Geographical Aware Routing Protocol Using Directional Antennas for NDN-VANETs (eGaRP) [7]. to evaluate MAKS's performance in terms of path losses, knowledge delivery ratio (KDR), and the number of packet retransmissions. In the simulations, we considered 50 vehicles equipped with sensing, communication, computation, and GPS modules. Each vehicle has a transmission radius of 250m. The vehicles move at varying speeds, ranging from 10 m/s to 35 m/s, in a specific direction toward destination. Each vehicle maintains a *MaFIB*, which comprises neighboring vehicles organized in decreasing order of DoC. We considered 4 randomly chosen consumers and four producers, varying the interest rates from 5 to 10 interests per second to evaluate the performance of the proposed work.The complete simulation parameters can be visualized in Table II.

To evaluate the performance of MAKS against the benchmark schemes, we considered the following metrics.

1) **Path partition rate (PPR):** PPR corresponds the proportion of instances in which an end-to-end communication path between the consumer and producer is "partitioned" during the knowledge delivery process.
2) **Knowledge Delivery Ratio (KDR):** KDR corresponds to the total number of Knowledge packets received against the total number of Interest packets sent by the consumer.
3) **Number of Knowledge retransmissions:** It denotes the total number of knowledge retransmissions against the transmitted knowledge packets.

A. Evaluation Results

1) Path partition rate (PPR): To assess the stability of knowledge delivery paths using MAKS's *MaFIB* and recovery mechanisms, we varied vehicle speeds from 10 m/s to 25 m/s, as shown in Fig 3. The results revealed that the proposed approach consistently outperformed the benchmark schemes in maintaining a stable reverse path for knowledge delivery. As illustrated, path partitioning increases with higher vehicle speeds; however, MAKS significantly reduces the PPR compared to NAMECENT and eGaRP. This improvement is attributed to MAKS's selective relay mechanism, which only involves potential relays with a high DoC to the sending vehicle. This approach substantially decreases the likelihood of path breakage. Furthermore, if a designated relay fails,

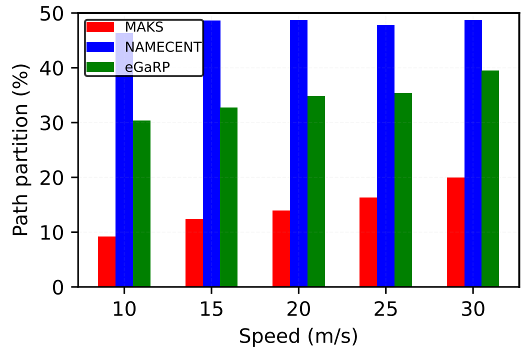

Fig. 3. Path partition as a function of speed

backup nodes automatically resume the communication until the knowledge successfully reaches the consumer, further reducing the frequency of path loss. In contrast, the eGaRP performs better compared to NAMECENT. The eGaRP scheme allows each node to maintain the geographical locations of its neighboring nodes. During knowledge transfer, the producer utilizes the breadcrumb path heading towards the consumer to hand over the requested knowledge. However, maintaining a reliable end-to-end path without considering vehicular characteristics is significantly complex in dynamic environments, resulting in frequent path losses and network congestion. On the other hand, NAMECENT lacks any mechanism to mitigate path losses. Consequently, if the potential forwarder fails to relay the knowledge, the entire communication process halts, preventing the consumer from receiving timely results.

2) Knowledge Delivery Ratio: The KDR achieved by the MAKS, NAMECENT and eGaRP schemes is presented in Fig 4. For analysis, we varied the number of vehicles from 10 to 50 within the region of interest. The results clearly demonstrate that MAKS outperformed the benchmark schemes, achieving above 90% KDR in all cases. This improvement is attributed to MAKS's use of a *MaFIB*, which is formulated based on vehicular dynamics (such as relative speed, distance, and DoC). The proposed scheme avoids blind broadcasting within the network by allowing only potential forwarders to participate in knowledge forwarding. The confined forwarding reduces redundant transmissions and congestion, thereby enhancing KDR. Additionally, the uniquely developed upstream and downstream recovery mechanisms further minimize the chances of knowledge loss, playing an effective role in boosting KDR. In contrast, the benchmark schemes lack a knowledge recovery mechanism to address knowledge delivery failures. Both NAMCENET and eGaRP blindly broadcast the interest packet in the absence of a potential relay node, leading to network congestion and collisions, which in turn reduces the KDR.

3) Number of Knowledge retransmissions: The number of knowledge retransmissions as a function of varying vehicle counts (i.e., 10 to 50) is presented in Fig. 5. The results clearly show that MAKS significantly reduces the number of retransmissions (i.e., redundant bits transmissions) by employ-

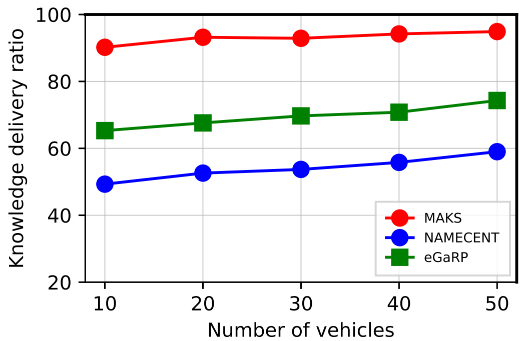

Fig. 4. Knowledge delivery ratio as function of number of vehicles

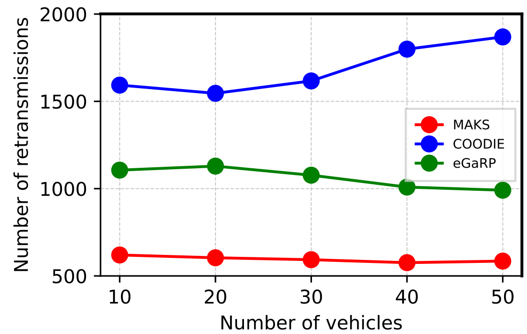

Fig. 5. Number of Retransmissions as function of number of vehicles

ing its uniquely developed downstream and upstream interest and knowledge recovery mechanisms. This mechanism enables neighboring vehicles of the upstream interest forwarder and downstream data forwarder to act as backup relays, preventing knowledge broadcast if the designated vehicle fails to continue forwarding.

In contrast, the number of knowledge retransmissions in eGaRP is lower compared to NAMECENT but significantly higher than in MAKS. The rationale is that eGaRP utilizes the geographical location of nodes as breadcrumbs toward the consumer. However, reverse path disruptions caused by the dynamic environment result in several packet retransmissions due to the unavailability of potential relay nodes, leading to higher knowledge retransmissions. On the other hand, NAMECENT employs a broadcast mechanism, which increases retransmissions when a potential relay fails to forward the packet. These factors significantly contribute to higher communication overhead, ultimately impacting the overall performance of the network.

V. Conclusion and Future Work

This paper presents MAKS: an efficient mechanism to ensure effective knowledge delivery in vehicular knowledge networks. MAKS leverages vehicular dynamics and introduces the *MaFIB* to ensure reliable knowledge transfer and reverse path stability in continuously changing environments. In addition, efficient interest and knowledge recovery mechanisms are designed to enable backup nodes to continue forwarding in the event of a potential relay failure. The proposed mechanism significantly reduces path losses and knowledge retransmissions in the network. Simulation results revealed that MAKS achieved an impressive KDR of over 90%, reduced path loss ratio by over 40%, and optimized the number of retransmissions by more than threefold compared to benchmark schemes.

In the future work, we plan to simulate the proposed work in ndnSIM (an ns-3-based network simulator). We will integrate OpenStreetMap and the SUMO mobility generator with ndnSIM to create a realistic urban vehicular traffic environment in order to analyze the benefits of MAKS in different traffic scenarios.

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