DyPoC : Enhancing VANET Efficiency through Tailored Transient Data Caching

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Abstract

In the context of Vehicular Ad Hoc Networks (VANETs), the integration of caching holds promise as a technique to improve user experience and lighten the load on the network's core infrastructure. The dynamic nature of vehicular networks, coupled with the intermittent connectivity of vehicles, requires innovative approaches for efficient data retrieval. While prior research has extensively focused on optimizing caching at the network edge, with Roadside Units (RSUs) as a key element, the potential of caching on individual vehicles has been underexplored. We address this gap by introducing DyPoC , a novel caching policy specifically designed for transient data scenarios. Transient data, characterized by its region-specific attributes, poses challenges not fully addressed by existing solutions, especially when dealing with in-car storage. DyPoC considers critical factors such as the distance of vehicles from the region of interest, data popularity, residual freshness, and vehicle trajectories to intelligently manage caching. We evaluate DyPoC using high-definition maps (HD maps) data, chosen for its manifestation of both regionality and expiration characteristics. Our evaluation shows how DyPoC provides a more effective and targeted approach for optimizing data retrieval in the dynamic environment of vehicular networks.

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1 Introduction

In contemporary transportation, VANETs have emerged as an innovative paradigm, seamlessly integrating vehicles into interconnected systems. Diverging from conventional networks, VANETs harness the mobility of vehicles to establish dynamic communication links, resulting in a decentralized and self-organizing network structure. Communication in VANETs encompasses Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), and Vehicle-to-Network (V2N) channels. V2V communication is particularly essential, enabling direct interactions between vehicles on the road. This facilitates the real-time exchange of information concerning traffic conditions, road hazards, HD maps, and other critical data. Such peer-to-peer communication constitutes the essence of VANETs, fostering collaborative efforts among vehicles to enhance safety and traffic efficiency. In tandem with V2V communication, V2I communication extends the network to infrastructure elements like RSUs, traffic lights, and other fixed installations along the route. This interaction augments the network's capabilities by providing resources at its periphery. Additionally, utilizing V2N communication, allowing vehicles to establish direct internet connectivity through cellular networks.

Within the dynamic VANET landscape, characterized by continuous information exchange for safety, efficiency, and an improved driving experience, caching emerges as a pivotal concept. The motivation behind caching in VANETs stems from the necessity to efficiently manage and retrieve data, addressing the unique challenges posed by vehicular networks. The intermittent connectivity and swift mobility of vehicles in VANETs create circumstances where traditional data retrieval methods may encounter limitations. Caching addresses these challenges by strategically storing and managing data at various points within the network. This proactive approach ensures that relevant information is readily available, reducing the reliance on constant real-time communication for data retrieval. Caching minimizes data retrieval latency by providing vehicles with access to frequently requested information locally. This is particularly crucial in time-sensitive applications such as autonomous driving, path planning, and collision warnings, where reducing communication delays can significantly enhance safety and efficiency. By locally storing and retrieving frequently used data, caching reduces the overall burden on the VANET infrastructure. This is beneficial for optimizing network resources, minimizing congestion, and ensuring efficient data dissemination. The intermittent connectivity in VANETs may result in temporary communication blackouts. Caching mitigates the impact of such disruptions by allowing vehicles to

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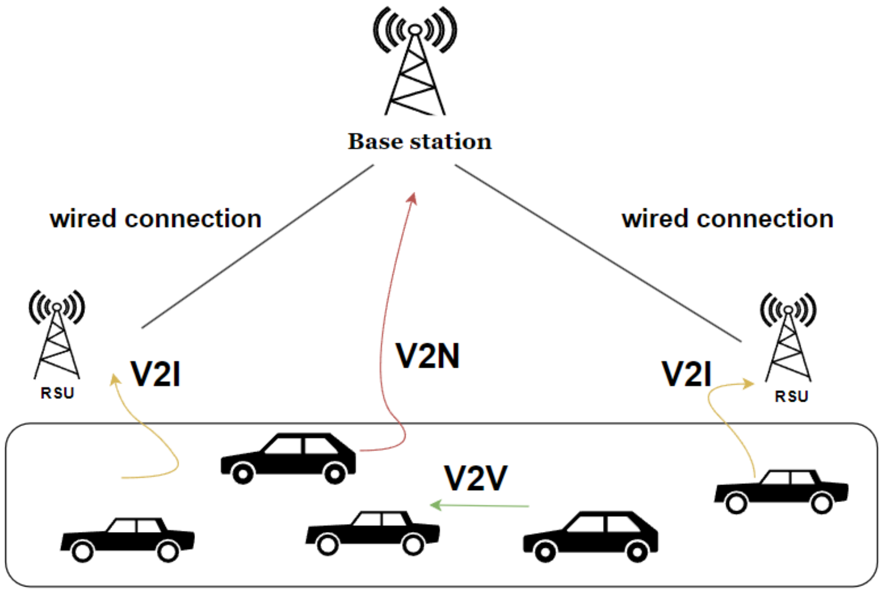

Figure 1. Communication in VANET

access cached data during communication gaps, ensuring a more reliable and continuous flow of information.

Numerous studies [1, 4, 6, 7] have extensively explored optimizing cache storage on RSUs. However, caching on vehicles has received relatively less attention [5, 9, 12]. Existing caching policies are often tailored for entertainment applications, where files commonly lack expiration times or region-specific relevance. In contrast, traffic information such as HD maps is inherently transient, valid for a limited duration, and exhibits regionality, being beneficial only for vehicles within a specific distance from the information source or the relevant region.

This paper introduces DyPoC (Dynamic Proximity-Aware Caching), a caching policy specifically designed for handling transient data such as traffic information. The proposed approach takes into account factors such as data popularity, freshness, proximity of vehicles to the area of interest, and their trajectories when making caching decisions. DyPoC demonstrates superior performance compared to baseline schemes, particularly in the context of HD map transmission, which is crucial for traffic information characterized by expiration and regional relevance. A noteworthy aspect of our caching strategy lies in the nuanced definition of driving distance, which is measured as the separation between the location where the content information is pertinent and the current position of the vehicle. This distinction is crucial for optimizing the caching process. We operate under the assumption that each vehicle possesses knowledge of its trajectory at every time slot, a realistic consideration in the realm of autonomous driving and assisted path planning. Our approach places greater importance on files associated with the future path, prioritizing them over files from previous routes, even in cases where they share the same distance value. This emphasis on future trajectory-related files contributes to the effectiveness of our caching policy.

2 DyPoC VANET Modeling

In our model, a city is represented as a graph featuring an intricate road network, with vehicles within the urban landscape equipped with foreknowledge of their trajectories. These vehicles depend on acquiring HD maps to facilitate their navigation through the city's complex road infrastructure. To accommodate the dynamic nature of traffic information, we make the assumption that each file containing pertinent data, such as HD maps, is characterized by essential attributes, including an expiration time, coordinates, radius of interest, and the name of the road associated with that specific traffic information. The crucial factor influencing the priority for requesting map data lies in the proximity of the information to the vehicle's present location. This approach ensures that the navigation system prioritizes obtaining data that is immediately relevant to the vehicle's current position, enhancing the efficiency and real-time adaptability of the overall system.

Each vehicle is mandated to possess HD maps encompassing the road network relevant to their intended routes, whether for path planning or autonomous driving applications. Consequently, vehicles diligently seek to acquire comprehensive sets of HD maps in advance of their journeys. The HD maps consist of two integral components: a static segment that remains invariant, and a dynamic component whose validity is limited to a specified timestamp. This dynamic aspect accommodates quasi-static data, maintaining relevance for a brief duration, typically a few minutes. When addressing the imperative need for real-time HD maps data, the adoption of crowd-sourcing or comparable methodologies becomes essential, as elaborated in [13]. The caching of such real-time HD maps data, however, proves ineffective due to its near-instantaneous expiration. The ephemeral nature of this data renders any caching efforts ineffective, as the information becomes obsolete almost immediately after generation, precluding the realization of benefits from existing caching strategies.

Various sources are available for obtaining HD maps, including other vehicles with cached map data, RSUs assumed to efficiently pre-fetch all necessary map data, and the cellular network connected to backbone servers responsible for map maintenance and updates. The optimal strategy for a vehicle is to procure HD maps from other cars traveling the same route, thereby reducing strain on the backbone network and ensuring lower latency. The next preferred option is to retrieve HD maps from RSUs when within their range. The least favorable scenario arises when a vehicle is in close proximity to a road and unable to access map data from either of these sources. In such instances, as shown in Figure 1, the vehicle must establish a direct connection to the cellular network, imposing a significant burden on the backbone network due to the volume of cars. To underscore this relationship, distinct costs are assigned to maps downloaded from different sources. This forms the foundation of an optimization problem centered on the caching and replacement policy of HD maps in vehicles, with the overarching objective of minimizing the combined cost associated with downloading HD maps for all vehicles.

In our communication setup, vehicles and RSUs employ the wave protocol for side-link signaling tasks, including the broadcast of necessary maps or the establishment of unicast channels for file transfers. This choice stems from the wave protocol being the prevailing communication standard for VANETs. However, due to the wave protocol's constrained bandwidth, it proves inadequate for HD maps transmission. To overcome this limitation, and in the absence of further standardization, vehicles, following signaling procedures, can utilize V2V and V2I unicast connections, akin to the principles of 5G Device-to-Device (D2D) connections. This adaptive approach ensures effective communication for HD map-related tasks while navigating the current constraints posed by bandwidth limitations in the wave protocol.

Our model also assumes that each vehicle will routinely dispatch requests for all HD maps along its designated route through one of the service channels within the Wave protocol. These channels are specifically designated for the distribution of traffic information and are universally recognized by all vehicles. The transmitted messages may encompass information about supported communication technologies, such as WiMAX, 5G, and others. In the event that a vehicle or RSU receives such requests and possesses the requested maps, they will initiate a unicast channel using one of the supported communication channels. Once a secure connection is established, the requested files will be efficiently transmitted to fulfill the vehicle's mapping requirements. This orchestrated process ensures a streamlined exchange of HD maps, enhancing the overall effectiveness of the communication framework within the model.

3 Dynamic Proximity-Aware Caching

In our caching policy, we selectively cache items with regionality only if they align with the trajectory of the vehicles. This determination is made by comparing the coordinates of a file and its radius of interest region to ascertain if there is any overlap with the current route of the vehicle. Additionally, files may include a field explicitly indicating the related road. For instance, an accident happening on a specific road may have that road name as part of the message. The logic behind this approach is that there is a higher chance of encountering other vehicles in our path that are interested in such items, enhancing the relevance and utility of the cached data.

If a file with regionality is in our path and has an expiration time, we further check if we can reach the radius of interest within the expiration time frame with the current speed and trajectory. If that is the case, we cache the item. This step ensures that we avoid caching items that would be invalid or provide irrelevant information, maintaining the integrity and usefulness of the cached data. When the cache reaches full capacity in our replacement policy, we calculate the value score for all cache items and remove the item with the lowest score. We use the following formula to calculate the value:

$$\text{value} = \frac{\text{residual life}}{\text{maximum residual life}} \times \frac{\text{normalized popularity}}{1 + \text{normalized distance} \times \alpha}$$

The first parameter influencing the value is the residual life of a file. This value is determined by subtracting the expiration time from the current time. If the result is less than zero, we consider it as zero. Subsequently, we divide this value by the maximum residual life in the entire cache to obtain a min-max normalized value between 0 and 1. The objective is to prioritize files with the longest validity periods, as they have a higher likelihood of being accessed before expiration. Despite a file being highly popular, if it has a close expiration date, retaining such an item may not be advantageous.

The second parameter influencing the value is the driving distance of the vehicle from the region of interest of the file.The goal is to prioritize items with closer proximity to the vehicle, as they are more likely to be beneficial. For example, HD maps of nearby blocks are more likely to be requested by other vehicles than those belonging to more distant blocks.

To further enhance this prioritization, we introduce an alpha variable that gives more importance to files belonging to the planned route ahead.If a file's region of interest is on the current path of the vehicle, it receives a value of 1. However, if it is not on the path, it receives a value of 2, effectively reducing its chance to stay in the cache. The logic behind this is that even if two items, for example, share the same distance, if one area of interest belongs to a passed route and the other belongs to the current path that we have not yet traversed, we prioritize the latter. To simplify the simulation, we consider each file to have a field indicating the related road, checking if this road is part of the current vehicle path.

Lastly, we consider the popularity of files by monitoring incoming requests. Vehicles maintain a dictionary that logs all broadcast communications they've heard in the past 3 minutes, recording the number of requests for each file. This approach allows us to identify files that are highly popular and sought after by multiple cars.If a file has no entry in this dictionary, it indicates either that it is not popular or that many other cars already have it. In either case, such files become strong candidates for removal from the cache, optimizing storage for more frequently requested and beneficial data.

4 Evaluation

We leverage OMNeT++ 6.0 as our primary network simulation tool for a study conducted on a 3x3-kilometer(Figure 3) map encompassing streets around Amir Kabir University, sourced from OpenStreetMap. Following preprocessing to address any road network issues and eliminate extraneous information, we employ the SUMO netconvert tool to transform the processed map data into a SUMO-compatible road network format. The subsequent step involves the utilization of the randomTrips tool from SUMO, which generates a set of random trips within the established road network by uniformly selecting source and destination edges. These generated trips form the foundation for vehicular movement in the simulation. To manage the routing of vehicles within the network, we utilize the duarouter tool from SUMO, which generates routes between specified source and destination edges for the participating vehicles in the simulation. It's noteworthy that, throughout the simulation, we maintain a consistent count of one hundred vehicles. Although vehicles may be dynamically created and destroyed during the course of the simulation, the total count is always upheld at one hundred to ensure a stable and controlled environment.

Additionally, we have strategically placed 25 RSUs along the roads and suitable locations, such as intersections. The distance between these RSUs ranges from 300 to 500 meters, a distance deemed appropriate based on literature. We use Veins to simulate the WAVE Protocol Stack and also as an interface between SUMO mobility and OMNeT. Vehicles will broadcast short wave messages periodically, once per second, requesting all the necessary HD maps. These requests will be transmitted over a designated wave service channel responsible for traffic information. The size of each request message is fixed at 1 kilobyte (1KB).

If any vehicle in the vicinity possesses one of the mentioned HD maps as requested in the broadcast, it will initiate the establishment of a unicast channel. This unicast channel aims to achieve bandwidth comparable to a 5G-based Device-to-Device (D2D) connection. The communication medium will experience Nakagami-m fading, introducing a stochastic fading model to simulate the real-world wireless channel conditions. In our simulation model, for the sake of simplicity, we assume that each vehicle has foreknowledge of all the roads it will traverse upon entering. Moreover, we break down HD map blocks into smaller chunks, where each chunk corresponds to a road segment. These chunks share a common road name and maintain a consistent size of 10 megabytes across the network. This simplifying assumption streamlines the simulation process, offering a more straightforward representation of the dynamics within the vehicular network.

We assigned varying costs of 100, 200, and 300 to the HD maps received from cars, RSUs, and cellular networks, respectively. At the conclusion of the simulation, we conducted a one-way ANOVA on the average cost of HD map retrieval for vehicles to assess whether there is a statistically significant difference among the caching policies. If statistical significance is detected, we proceed to utilize the Tukey Test for pairwise comparisons to obtain a more detailed understanding of the performance differences between the caching policies. This process is repeated with various seeds to ensure that the results are valid.

The preliminary results, as depicted in(Figure 2), reveal the superior performance of our caching policy compared to baseline cache policies when the cache size is appropriately configured. Notably, when the cache size is insufficiently short, we observe no statistically significant differences between various caching policies. This is attributed to the limited number of cache items, rendering their impact on the system minimal. Conversely, in cases where the caching size is excessively high, all policies demonstrate similar behavior, as the ample space availability negates the immediate necessity for cache item replacement.

5 Limitation & Future Work

Our work has not considered the privacy implications tied to the transmission of HD maps. This is a critical oversight, especially given that the broadcast of vehicle request patterns for HD maps has the potential to unveil destinations and potential routes of vehicles, presenting substantial privacy concerns. To address this gap, it is imperative that we take proactive measures to incorporate safeguards ensuring

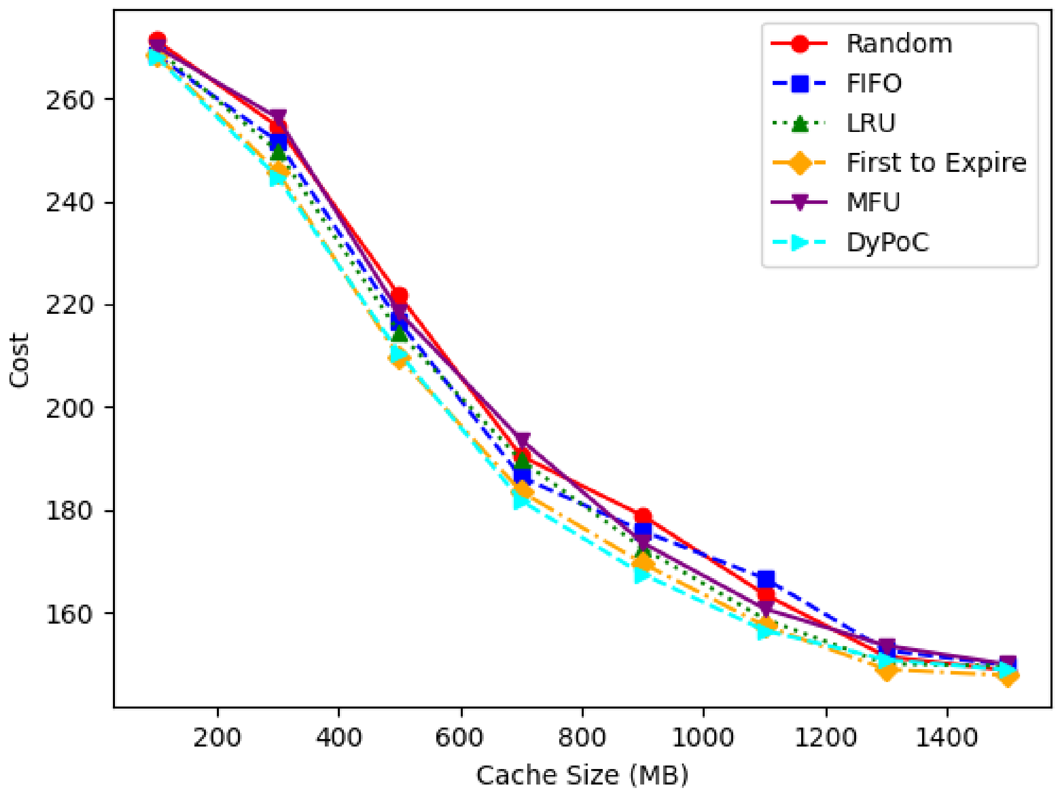

Figure 2. Simulation Results

the privacy of users and their travel information within the framework of our HD map transmission system.

Also, The current state of HD maps lacks standardization, with major companies such as Google and TomTom each providing their own HD map services featuring diverse formats, sizes, and included information. This lack of uniformity introduces a significant challenge for researchers, as precise information and map sizes are not publicly available and vary between services. Furthermore, this absence of standardization restricts vehicles from using information from specific services, limiting the exchange of information and collaborative efforts.

6 Related Work

Most existing research on edge and IoT caching predominantly focuses on caching intransient data, creating a noticeable gap in addressing caching for transient IoT data. A few notable exceptions include works by authors in references [10] and [11], who incorporated data transiency into their caching policies for Internet content routers. They introduced an analytical model that considers variables like the lifetime of data items and the rate of received requests, providing insights into the trade-off between multi-hop communication costs and data freshness. In [14], another approach was proposed—a cooperative in-network caching scheme for information-centric networking IoT—based on the least recently used (LRU) replacement policy. This scheme considered the data lifetime of IoT data items by establishing a threshold for each node, determining whether to cache the data or not. Amadeo's Freshness-Driven Caching (FDC) Strategy [2] stands out as a noteworthy caching strategy explicitly designed for transient data in VANETs. The FDC Strategy takes into account the residual lifetime of content in making caching decisions. In a related work [3], Amadeo further investigates caching decisions considering residual lifetime, popularity (measured as the ratio of requests for a file to the maximum number of requests), and availability (expressed as the number of hops for content retrieval). Ostrovskaya's work [8], considers freshness, frequency of requests for cached data, and the distance between the car and the location where the file was cached for making caching decisions. To the best of our knowledge, our work distinguishes itself by being the first to consider the trajectory

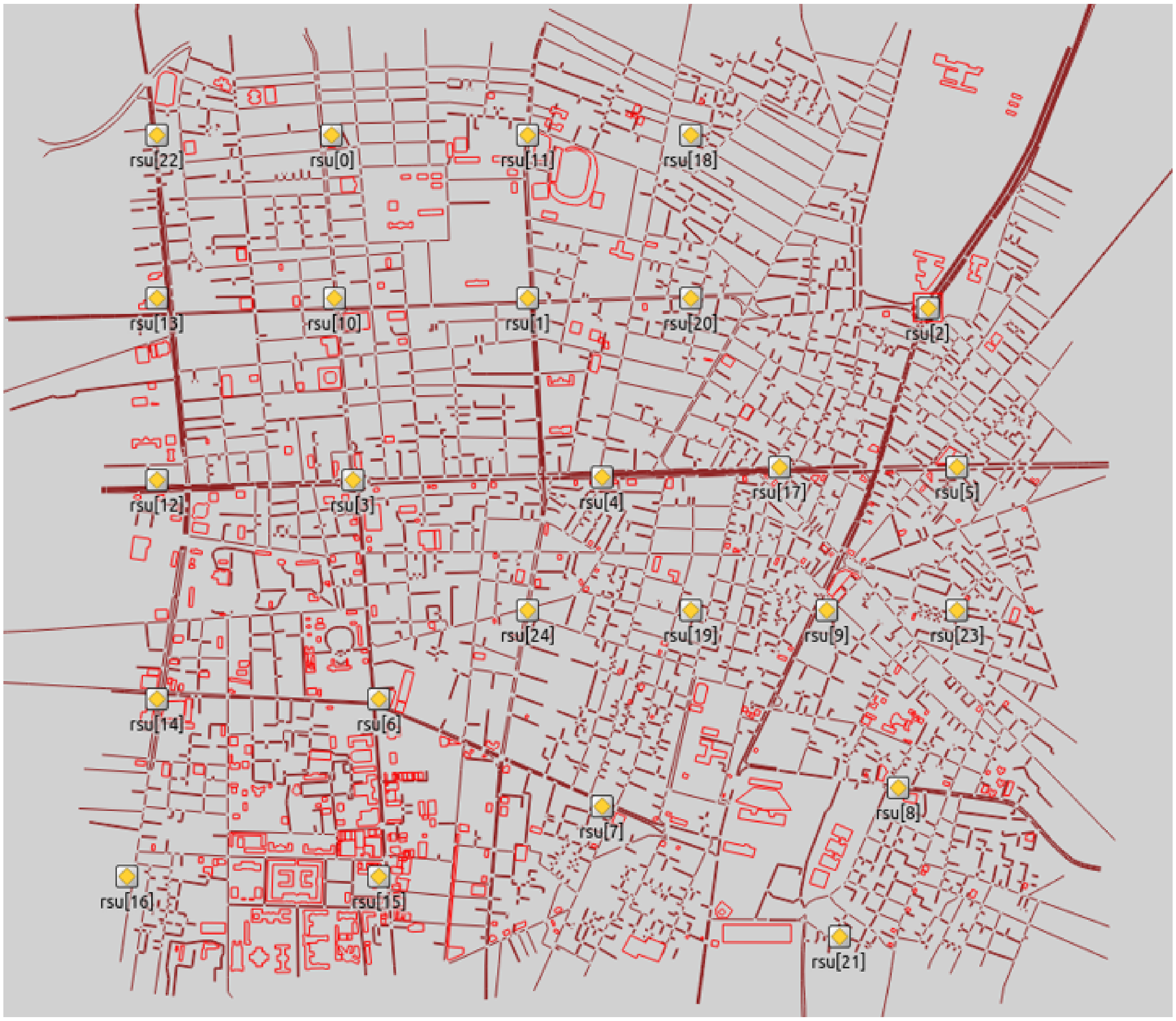

Figure 3. Simulation setup

of cars, popularity, and the distance of vehicles to the area of interest when making caching decisions for in-car storage. This holistic approach aims to enhance the efficiency and effectiveness of caching strategies in dynamic vehicular environments.

7 Conclusion

We have presented DyPoC , a tailored caching policy specifically designed for VANETs data, dealing with data characterized by expiration time and region-specific relevance. Our approach harnesses critical parameters such as vehicle trajectory, file popularity derived from monitoring request broadcast transmissions, and the proximity of a vehicle to the region of interest, culminating in the formulation of an intelligent caching policy. We subsequently assess the efficacy of our policy within the domain of HDM transmission, a pivotal category of traffic information. The results obtained from simulations unequivocally demonstrate the superior performance of our caching policy in comparison to baseline alternatives, thereby highlighting its effectiveness in optimizing data caching for VANETs.

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