On the Performance Evaluation of VANET Routing Protocols in Large-Scale Urban Environments (Poster)

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***Abstract*—With the increasing capabilities of vehicular communications technology, VANETs (Vehicular Ad-Hoc Networks) have witnessed a significant development. Key to the establishment of value-added services and applications is the design and development of routing protocols. This article studies the effects that mobility, road topology and network applications have on the performance evaluation of VANET routing protocols. Specifically, we evaluate the performance of three known and highly established VANET routing protocols by employing realistic mobility from a large-scale urban topology and imposing network load via an exemplary VANET-based, traffic query, application. We compare the results against results obtained by following the simplistic evaluation approaches often available in the literature. We argue that results stemming from such a realistic evaluation approach, increase the possibility of identifying problems as well as implications in the design of routing protocols that need to be considered and addressed for achieving optimal performance.**

I. Introduction

In an effort to combat real-life transportation problems such as accidents, traffic jams, fuel consumption and pollutant emissions, Inter-Vehicle Communication (IVC) and subsequently the concept of Vehicular Ad Hoc NETworks (VANETs) have emerged as a promising field of research. Advances in wireless and mobile ad hoc networks (MANETs), global positioning systems and sensor technologies serve as the ground work for the development of innovative vehicle-to-vehicle(V2V) applications and services [1] with great potential for improving the safety and quality of daily commute.

It is widely acknowledged, that one of the key factors to the successful establishment of VANETs and the provision of effective solutions to the aforementioned problems is the design and development of *routing protocols*. However, due to the inherent characteristics of the vehicular environment [2], traditional routing protocols for MANETs cannot be applied to VANETs. Thereof, during the past years a number of new routing protocols have been explicitly proposed for VANETs that take under consideration these unique characteristics and aim to route information among vehicular and road-side nodes [3], [4]. The main goal of routing in VANETs is to transmit data from a single source to a single destination (unicast) or to a specific geographic region (geocast) using an amalgamation of wireless multi-hop and carry-and-forward techniques. However, evaluating the effectiveness and efficiency of such protocols is challenging. Real IVC test-beds in the likes of [5], [6] are not widely available and easily accessible. Furthermore, their low penetration rate, high complexity and operational costs, render large-scale evaluations infeasible. Therefore computer simulations are the preferable method of achieving performance evaluation of VANET routing protocols and are expected to remain the de-facto evaluation tooling in VANET research for the next several years.

A. Motivation

Despite the availability in the literature of what is now a substantial number of VANET-dedicated routing protocols [4], as well as the availability of several simulation frameworks [7], the community has yet to adopt an approach that enables a thorough and realistic performance evaluation. The majority of proposed protocols are envisioned to provide data routing for a range of applications/services, specifically for the demanding *urban vehicular environment*. However, the approaches which are traditionally followed during the evaluation phase are not reflective of the characteristics of such an environment.

Specifically, a number of research works evaluate proposed protocols in the absence of realistic *vehicle mobility* and/or *road topologies*. In reality, the underlying urban road topology and vehicle mobility will respectively dictate the structure of the VANET and dynamics of V2V communication. Consequently, the use of realistic mobility and road topologies are key to any simulation based VANET routing protocol performance evaluation. Particularly, the realistic representation of vehicular traffic, both from a microscopic (individual vehicle physical characteristics and behavior), as well as a macroscopic level (flow patterns based on diurnal cycles, population synthesis and activities) should become an indispensable component of every simulation study [8].

Although other research works correctly evaluate protocol performance under realistic road topologies and vehicle mobility, they do so in the absence of *realistic applications*. In contrast to the simplistic and naive applications employed in such studies, realistic applications generate network traffic in a manner that mimics the behaviour of envisioned IVC systems such as safety, navigation and infotainment. The utilization of these realistic applications during simulative analysis enables one to observe the characteristics and protocol behaviour under network traffic conditions that closely match the ones that would be faced in a real-life deployment.

Finally, due to the unavailability of *exemplary implementations* of various VANET routing protocols, evaluations are very often performed against MANET protocols (i.e GPSR, AODV), which are inherently unsuitable for the dynamic vehicular environment [9], [10].

Taking into account the research efforts on VANETs that constantly work on increasing the level of detail and accuracy of all underlying components so as to provide optimum performance and reliable V2V communication, it is crucial to evaluate routing protocols on a reasonable size vehicular network using realistic mobility and applications.

B. Contributions

We evaluate and compare the performance of three highly established VANET routing protocols GPCR [11] (multi-hop protocol), VADD [12] (carry-and-forward protocol) and LOUVRE [13] (overlay protocol), under different urban scenarios of varying size and realism. These protocols are cited in many research studies and are known as good performers in their respective classes of routing protocols [3], [4], [14]. Initially, we examine their performance following simplistic approaches undertaken in the majority of the literature so far. Consequently, we combine highly realistic vehicle mobility in a large-scale urban topology as well as network traffic generated from an exemplary traffic query application. By doing so, we aim to evaluate their performance under conditions that strive to resemble as closely as possible the behavior and the environment that each single car would face in reality. We argue that results stemming from such a realistic and complete scenario, increase the possibility of identifying problems as well as implications in the design of routing protocols that need to be considered and addressed for achieving optimal performance. To the best of our knowledge, this is the first research work in the related literature that not only brings under one roof three highly established routing protocols that have been proposed specifically for VANETs, but also evaluates their performance in a realistic manner.

The remainder of this paper is organized as follows: Section II presents the Related Work. Section III presents a VANET-based traffic query application utilized in the analysis section. Section IV performs an analysis of the performance of the examined protocols under different scenarios. Finally, Section V concludes this paper.

II. Related Work

Our work is inspired by the rich body of prior work on VANET routing and data dissemination protocols. Examples of such protocols (presented in chronological order) include: GPCR [11], VADD [12], CAR [15], D-MinCost & D-Greedy [16], LOUVRE [13] and SADV [17].

VANET simulations require realistic wireless network and mobility models. However, the development of an open and flexible simulation platform that will integrate wireless communications and road traffic simulation platforms in an environment that is easily tailored to specific situations allowing performance analysis of cooperative ITS at urban level, still remains an open issue (i.e., see iTetris EU project [18]). For the evaluation of *GPCR* [11] the authors employed realistic mobility traces from 955 vehicles moving within the real road topology of Berlin, Germany. However, only a very small fraction of the total vehicles available (10 randomly selected vehicle pairs) exchange packets for a short period of time (20 packets over 5 seconds). Likewise, the evaluation of *CAR* [15], utilizes realistic mobility traces from a large number of vehicles moving in and around the city-center of Zurich, Switzerland [9], while 20 vehicles generate traffic with a rate of 4 packets/s. Despite the utilization of realistic mobility in the above works, the information exchange model is simplistic and not representative of a VANET application, and any use of it introduces subsequently the risk of obtaining erroneous performance results. Furthermore in [9], all source-sink pairs remain within the evaluation area for the whole of the simulation duration, an assumption which does not hold true in reality. Ongoing communication flows can break, due to the decision of either the source/destination node to abruptly depart the VANET, or due to the effects of network partitioning. Consequently, it is essential that the evaluation process demonstrates the ability of any routing protocol to recover and handle appropriately such situations. The mobility traces from Zurich are also utilized for the evaluation of *D-MinCost & D-Greedy* [16], nevertheless vehicles exchange on total only 100 messages in the whole duration of the simulation. In [12], the authors evaluate the performance of the delay-tolerant VADD protocols in a road network with a grid layout, derived and normalized from the U.S. Census Bureau TIGER [19] database. Since TIGER does not provide information concerning one-way streets, therefore all streets in the topology were considered two-way, an assumption which ultimately affects the structure and dynamics of the IVC. The evaluation is based on a maximum of 210 vehicles that as in the case of [9], they unrealistically update their trip destinations in order to remain in map for the whole simulation duration. In addition, only 15 traffic sources (vehicles) are available that constantly send packets to two stationary sites. Similarly, the performance of LOUVRE [13] has been evaluated in a small road topology, derived from the TIGER database. In contrast to [12], the authors employ realistic mobility using VanetMobiSim for 100 vehicles. SADV [17] is evaluated on a slightly larger grid topology than VADD and LOUVRE, where vehicles take random trip until the end of the simulation. In contrast to VADD, vehicles generate packets to random destinations, nevertheless the total packet generation rate in the map is constrained to 10 packets per second.

An important aspect of simulative testbeds is the realism of the mobility traces. In the literature, only very few realistic mobility trace datasets are publicly available(i.e. [9]). To the best of our knowledge, the largest and most frequently updated dataset in the literature is the one available by the TAPAS-Cologne project [20], of the Institute of Transportation Systems at the German Aerospace Center (ITS-DLR). By combining real-world data including the road topology, population

	[11]	[12]	[15]	[16]	[13]	[17]	Our Work
Realistic Mobility	$\surd$	x	$\surd$	$\surd$	$\surd$	x	$\surd$
Real Topology	$\surd$	o	$\surd$	$\surd$	o	o	$\surd$
Realistic Application	x	x	x	x	x	x	$\surd$
Simulation Area(Km)	6x4	4x3	25x26	20x10	1x1	4x5	20x20
Max. Vehicles	955	210	50 v/km	1000	100	300	4670
Comparison with other VANET protocols	x	x	x	x	$\surd$	$\surd$	$\surd$

TABLE I: Performance Evaluation Approach details comparison
($\surd$ = Uses, o = Partially Use, x = Not Uses)

demographics and traffic demands, and providing them as input to the well-known and established SUMO [21] mobility simulator, the project generated mobility traces that closely describe the traffic within the city of Cologne, Germany for 24 hours.

In contrast to the above studies, this work evaluates the performance of the three VANET protocols (GPCR, VADD, LOUVRE) in a large-scale urban environment. Particularly, for the purposes of our study, we consider the improved version of the initial TAPAS-Cologne dataset, available in [8]. Moreover, to further observe the capabilities of each protocol, we evaluate them under network traffic generated by a realistic VANET application. Table I provides a comparison of the approaches taken by the above research works in evaluating the performance of the VANET routing protocols. The last column presents the details of the approach taken in this paper.

III. V-Radar: A VANET-based Traffic Query Application

A. V-Radar

This section introduces a VANET-based, traffic query application, called *V-Radar*, which will be utilized in the analysis presented in Section IV. The objective of using such an application, is to present each routing protocol to a environment in which the network load and demand will closely resemble the one that will be imposed by future VANET applications.

V-Radar extends upon our initial concept [22] of a VANET-based, traffic information system that works in tandem with on-board navigation/route planning systems. We envision the ability of an IVC-enabled vehicle to provide its driver with valuable, close to real-time, traffic information by issuing location-dependent queries to other vehicles. Particularly, we assume that the driver and occupants of any vehicle would like to minimize the travel time en-route to their destination. Taking into account that each vehicle is aware of the road-network topology through on-board digital maps and its current location through a global positioning system, the goal of V-Radar is to identify the road-path to a destination that imposes the minimum travel time. To discover such road-paths we propose a traffic information query application that resembles a *directional-scan-radar*.

Assume Vehicle X on Figure 1 is driven on *Road A* and wishes to follow the road-path to its destination D with the minimum travel time. However, X would also like to know the prevailing traffic conditions for the other available paths to D, in case a route change is required. Through its knowledge of the road network, X can calculate and consequently rank the K possible road-paths from the next intersection to the intersection which is closest to D.

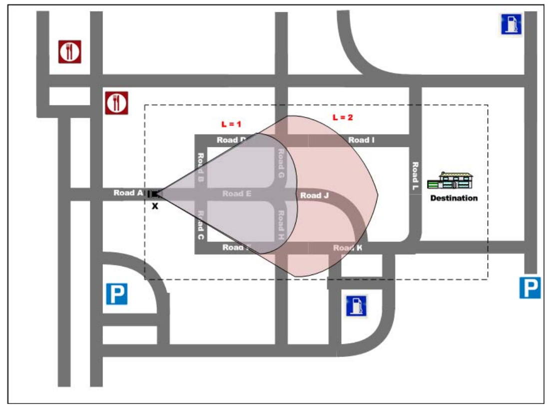

Fig. 1: V-Radar: A VANET-based Traffic Query Radar Application

At a predefined distance prior entering *Road A*, X issues *LookAhead (L)* queries at a selected rate (R) towards all these possible road-paths. *LookAhead* queries are propagated to a certain depth L in each of the identified road-paths and obtain the traffic conditions of all the roads up to and including the specified depth. L, K and R are parametrised values that can be adapted intelligently by the vehicle in order to avoid swarming the network with data packets, while at the same time maintaining acceptable levels of traffic information quality.

Returning to the example of Figure 1, if X would like to know the traffic conditions in all road-paths within the boundary up to 2 roads ahead of its current position, then the look ahead value will be set to $L = 2$ and the following traffic queries will be generated: Query_1:{Roads B,D,I}, Query_2:{Roads E,G,I}, Query_3:{Roads E,J,K}, Query_4:{Roads E,H,K} and Query_5:{Roads C,F,K}.

Consequently, generated queries are forwarded in a multi-hop fashion to each individual road in a given path, where the required traffic information is retrieved either with the cooperation of other vehicles (see the concept of VAHS in [23]) or by the road-side infrastructure (i.e intelligent inductive loops). Assuming that X's driver chooses to follow the path comprised of Roads A→E→G→I, the next query cycle can be initiated either before entering any of the intermediate roads or prior reaching any road on depth $L - 1$. In the example, if the latter query cycle frequency is used, V-Radar will initiate another set of look-ahead queries while the vehicle is moving on *Road E* and prior reaching the starting intersection of *Road G*. This process iterates until X reaches its destination D. We assume also the existence of a location service which is utilized to obtain the current geographic location of the query-source vehicle.

We acknowledge that issuing individual queries/replies to and from each road in a given path to the destination can lead to a substantial increase in the imposed network overhead. Since this paper introduces the *directional-scan-radar* for the purpose of generating realistic network traffic for the analysis in Section IV, we will leave mechanisms for mitigating the aforementioned side-effects as our future work.

IV. VANET Protocol Performance Analysis

A. Simulation Setup

For the purposes of the evaluation, GPCR, VADD and LOUVRE were implemented from scratch under ns-3.11 [24], trying to remain as accurate as possible given the information provided in the original articles [11]–[13]. For baseline comparison, we include in our evaluation the well-known AODV protocol [25]. AODV is a MANET reactive routing protocol that builds routes on demand, and is often used in the literature when evaluating the performance of VANET routing protocols. The reasoning behind using AODV here, is to depict to the reader how the performance of a MANET protocol compares against the performance of VANET dedicated protocols in the vehicular environment. Based on the findings of [26], each vehicle broadcasts a HELLO beacon at a rate of 10Hz. Data-rate was set to 3Mbit/s, and all the PHY and MAC properties conform to IEEE 802.11p [27]. Table II presents all the parameters that were utilized in the network simulator throughout the evaluation.

B. Examined Metrics

We reside in the following metrics in order to evaluate the performance of VADD, GPCR and LOUVRE.

- *Packet Delivery Ratio:* the ratio of queries received by the destination vehicles/sites to those generated by the source vehicles.
- *Number of Hops:* the average number of vehicles a query has traversed in order to reach the destination. For round-trip queries, the total number of hops (source-destination-source) are calculated
- *Average Delay:* the average difference between the time a traffic query was generated by the source node and the time the reply to the source node was received. Dropped or lost queries are not included.

Note that the results depicted in this section, account for the average values of each of the above metrics, calculated over 5 runs for each simulation scenario, with different random number seeds.

We employ the following scenarios to determine to what extend the road topology, vehicular mobility and the application (information exchange model) affect the performance of the above VANET protocols.

C. Typical Scenario

Initially, to understand to what extend the road topology and consequently vehicular mobility affect the performance of the above protocols, we opted to experiment on a scenario typical to what is used in a number of research works in the bibliography. The scenario consists of a 4Km X 3Km grid-layout road topology extracted from the U.S. Census Bureau TIGER [19] database, with 18 intersections and 26 bi-directional roads. Intersections are not controlled by traffic lights, therefore vehicle turns (straight or left/right-turns) are dictated by the prevailing traffic conditions at the intersection. To simulate vehicular traffic conditions similar to that of an urban environment, all horizontal roads are set as high-speed roads with a speed limit of 80Km/h, while all vertical roads are set as local roads with a speed limit of 55Km/h. We feed the road network to SUMO [21] and generate random trips for 250 vehicles, making sure that all of them remain in the map for the whole of the simulation area. We provide two variations of this typical urban scenario, one using a simplistic information exchange model that mimics a parking place reservation application and one using the V-Radar application. Below we present the results of these two variations.

Parking Place Variation - we assume that a number of vehicles would like to make a reservation to a specific parking-lot. Four static nodes are placed at the corners of the grid road topology to simulate such a site. Among all vehicles, 15 of them are randomly selected to send Constant-Bit Rate (CBR) data packets to these 4 static sites. No reply is send back to the vehicle for a reservation and duplicated requests arriving at a site are simply discarded. We perform different simulations to study the effect of varying the data sending rate (as per Table II).

It can be observed in Figure 2, VADD achieves the highest packet delivery ratio among all protocols. This is primarily due its capacity to cache packets (a process known as carry-and-forward) when: (i) no other vehicle exists in the vicinity of the current packet carrier (i.e. network fragmentation), or (ii) none of the carrier's existing neighbors is considered to be a better candidate to uptake the role of forwarding the packet to its destination. Specifically, in this occasion, where the underlying road topology layout and sparse vehicle density constantly drive the network to fragmentation, VADD performs better by buffering packets until network connectivity is established. On the contrary, GPCR and LOUVRE do not support carry-and-forward, hence they exhibit a much lower packet delivery ratio. When such of the aforementioned conditions are encountered in the network, both GPCR and LOUVRE silently drop the packet.

The substantially higher packet delivery delay that VADD exhibits in Figure 3, in contrast to the delay imposed by the other three protocols, is attributed to the additional time a packet spends in a vehicles' cache. Our study revealed [1] that the increased packet delay in conjunction with the better packet delivery ratio seen previously, stems from the fact that VADD can serve packets for which their origin vehicle is geographically further away from the destination site. Similarly, the very low packet delivery delay ($\leq$1 sec) exhibited by GPCR, LOUVRE and AODV, is due to the fact that all

[1]Figure omitted in the interest of space

	GPCR	VADD	LOUVRE	AODV
Protocol Variation	GPCR-CC	H-VADD	N/A	N/A
Vehicle Transmission Range	300m (802.11p)			
Propagation Model	Nakagami Propagation Loss			
Simulation Time	1000s (200s warm-up)			
Data Rate	3Mbit/s			
Beacon Generation Rate	10Hz with some jitter			
Packet Generation Rate (pkt/sec)	0.2, 0.4, 0.6, 0.8, 1.0			
Packet Size	1KB			
Packet TTL	64			
Cache TTL	128 sec (where applicable)			

TABLE II: Network Simulation setup parameters

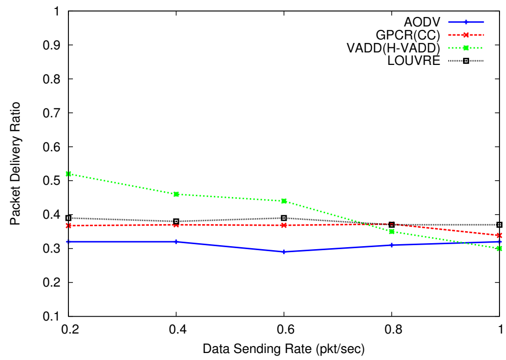

Fig. 2: Packet delivery ratio as a function of packet sending rate - Typical scenario for parking place reservation

successfully received packets were the ones that either got generated at proximity of the destination or on the very few times where mobility was such that it permitted end-to-end connectivity between geographically distant nodes.

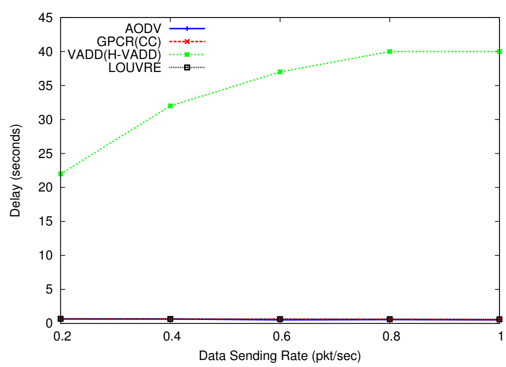

Fig. 3: Packet delivery delay as a function of packet sending rate - Typical scenario for parking place reservation

As depicted in Figure 4, data packets in VADD traverse on average the same number of hops as packets that are routed with the aid of GPCR, LOUVRE and AODV. This is a clear indication that carry-and-forward mechanisms do not affect the number of hops during an end-to-end communication, they merely assist by enabling the bridging of network fragments. We note that the average 5-7 hops that a packet is required to traverse en-route from source to destination are indicative of the dimensions of the respective underlying road topology and a wireless transmission range of approximately 300m.

Implications: From the above findings, it is evident that in a scenario such as the parking spot reservation where there is delay tolerance, carry-and-forward protocols in the likes of VADD are highly suitable. Such protocols increase the probability that a request will be propagated to its destination even with some acceptable delay. Most importantly though, they indicate that the performance of non carry-and-forward protocols (i.e GPCR and LOUVRE) can be underestimated due to conditions of poor network connectivity induced either by low-vehicle density (considering the 250 vehicles in a 4x3 Km area) or unrealistic mobility. These two factors can cause network fragmentation, which inevitably will result in packet drops and consequently low packet delivery ratio.

V-Radar Variation - In light of the above we extend the evaluation of the typical urban scenario, by introducing a second case, where all vehicles are installed with the V-Radar traffic information application presented in Section III. Prior to initializing the simulation, all vehicles are pre-loaded with a map of the underlying road topology (a directed graph) and traffic statistics computed by SUMO.

In the V-Radar scenario, once a vehicle enters a new road, it starts generating queries (with *LookAhead (L)*) to all roads that make up the available road-paths leading to its destination in order to identify the prevailing traffic conditions. A vehicle calculates all the K-shortest road-paths from its current position to its destination by running Yen's K-shortest path algorithm [28] on the road topology directed graph. For the purposes of this evaluation we select a value of $K = 3$ and $L = 2$. In addition, data packets containing traffic information queries are generated with a CBR rate(R) between 0.2 and 1.0 packets per second (incremented by 0.2).

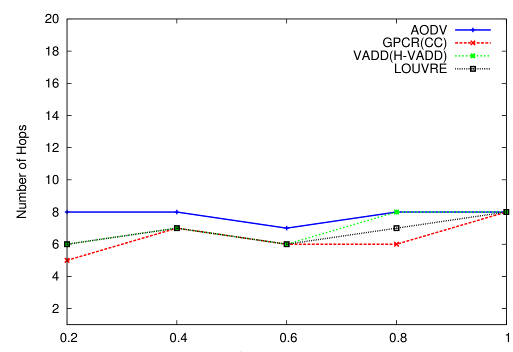

Fig. 4: Number of Hops as a function of packet sending rate - Typical scenario for parking place reservation

Once a vehicle approaches the end of the road, it stops generating queries until it crosses an intersection and enters a new road. Queries are propagated to the destination roads, where a reply is generated and immediately routed back to the source node. In case that no vehicle exists in any of the destination roads, the packet is dropped. This road query process is performed continuously, until 100 seconds prior to the simulation end in order to allow for all vehicles to process any packets which are still propagating the network (queued queries or replies en-route to the source vehicle).

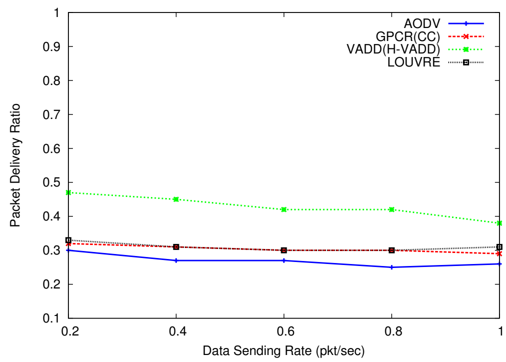

Fig. 5: Packet delivery ratio as a function of packet sending rate - Typical scenario with V-Radar

Implications: In contrast to the previous case where all vehicles were sending packets to a fixed site, here we observe the performance of all protocols to degrade extensively. This is due to the round-trip that each query has to perform; queries need to be forwarded at first from the source vehicle to the destination road - there, once a query reply has been formed it has to be routed back to the query source node. In addition a number of queries might be send towards some roads with no vehicles at all. We notice that AODV exhibits the lowest packet delivery ratio among all protocols and this is accounted to its backward learning mechanism. Specifically, when an node receives a query en-route to the destination road, it creates a record to its routing table containing the address of the previous node (previous hop) from which the query arrived. Upon the query arrival at the destination road, a reply is formed and send back to the origin vehicle through the path which is formed by the previous hop records at each intermediary node. However, due to the high dynamics of the vehicular environment, the structure of inter-vehicle communication changes rapidly [2], thus the backward learning process is not efficient and results to several packets being dropped due to the expiration of backward links. On the contrary, GPCR does not maintain a routing table. Queries and query replies are routed from the origin node to the destination road and back using ad hoc, geographic greedy forwarding. As in the case of sending packets to a fixed side, GPCR can fail when the VANET becomes fragmented and greedy forwarding in no longer viable. On the contrary, VADD is able to counteract such fragmentation through its aforementioned carry-and-forward capability. However, in the case where traffic does not have a relatively stable state (as in the typical example above), VADD might underestimate in the process of selecting the best path towards the destination. This can impose additional delays on a query. In an application such as V-Radar, where vehicles would like to know the traffic conditions of the roads further ahead in a relative short amount of time, the packet delivery delay exhibited by VADD is considered to be unacceptable. As identified in [29], Traffic Flow and Enhanced Route Guidance and Navigation applications such as V-Radar, should have a maximum allowable latency of 1 second. A packet delivery delay in excess of 40sec which is evident for VADD in Figure 6 is not considered to be acceptable since it increases the probability of acquiring stale traffic information.

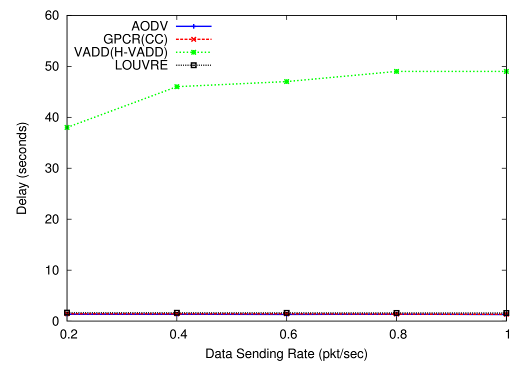

Fig. 6: Packet delivery delay as a function of packet sending rate - Typical scenario with V-Radar

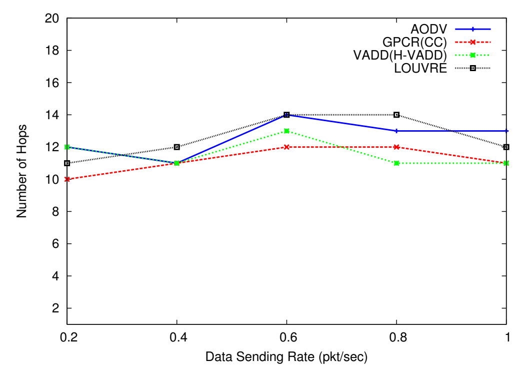

Fig. 7: Number of hops as a function of packet sending rate - Typical scenario with V-Radar

Despite the presence of V-Radar, the above two cases were performed under a simple road topology with unrealistic, low-density mobility. Since mobility is key to the dynamics and structure of VANETs - and consequently to the proper-function of any application and service relying on such networks - the performance of AODV, GPCR, VADD and LOUVRE stemming from the above evaluation might be considerably underestimated. The next section aims to investigate this hypothesis.

D. Large-Scale Urban Scenario

In order to evaluate AODV, GPCR, VADD and LOUVRE in a large-scale urban scenario, we employed the TAPAS-Cologne [20] realistic mobility dataset from the Institute of Transportation Systems at the German Aerospace Center (ITS-DLR). The TAPAS-Cologne scenario contains mobility traces that describe with very high realism the vehicular traffic within and around the city of Cologne (Germany) for a period of 24 hours (the dataset covers approximately $400Km^2$ and 4500 roads). For the purposes of our study, we consider an improved version of the initial TAPAS-Cologne dataset, available in [8]. Specifically, we utilize a reduced version of this improved dataset, which contains vehicle trips between 6:00am and 8:00am. We study the first 1000 seconds of this interval, in which a total of 4670 vehicles were emitted in the road topology.

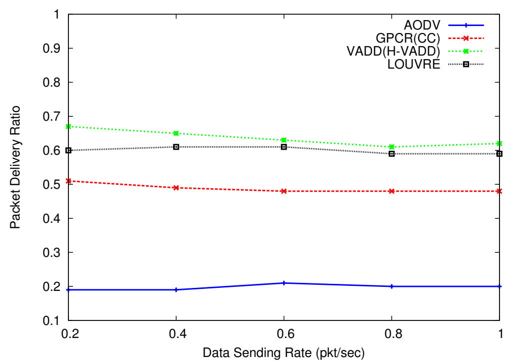

Fig. 8: Packet delivery ratio as a function of packet sending rate - TAPAS/Cologne

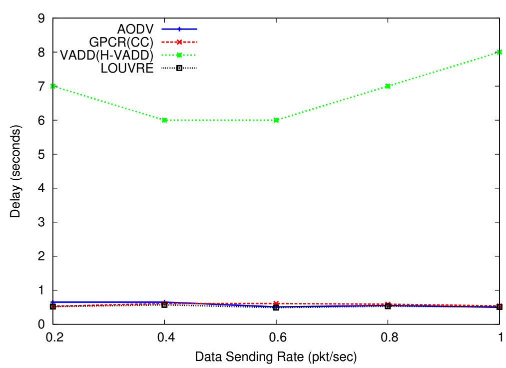

Fig. 9: Packet delivery delay as a function of packet sending rate - TAPAS/Cologne

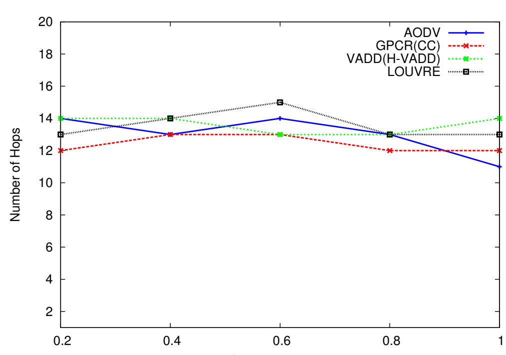

Fig. 10: Number of hops as a function of packet sending rate - TAPAS/Cologne

In addition all vehicles are installed with the V-Radar traffic application and generate queries as described previously in Section IV-C.

By looking at Figure 8, we immediately observe the profound effect of mobility in the performance of the studied VANET routing protocols. Because of the realistic microscopic dynamics of each individual vehicle, the correct distribution of vehicle flows in a macroscopic level and the high density in the underlying road topology, the performance of GPCR, VADD and LOUVRE improves significantly allowing traffic queries and their respective replies to be routed more efficiently and effectively. Even for a non-carry and forward protocol such as LOUVRE, realistic mobility allows packet delivery up to approximately 60% in comparison to the 35% in the typical scenario with V-Radar. Since traffic conditions on the TAPAS-Cologne scenario do not change as rapidly as those in the typical scenario (i.e. traffic is stabilized), the overlay network in LOUVRE is able to maintain a global vision of the density distributions on roads, and thus it can route information more efficiently than GPCR. Since the latter is not aware of any important information concerning the underlying road topology and consequently tries to route packet from source to destination in a greedy fashion, it can encounter local maxima situations such as empty roads from which it cannot recover and eventually cause packets to be dropped. Despite that, the performance of both LOUVRE and GPCR in the TAPAS scenario outperforms their performance in the typical scenario with V-Radar. Due to the better end-to-end connectivity because of high vehicle density, greedy forwarding can achieve a higher packet delivery.

Implications: The data buffering ability of VADD, as well as the repetitive process at each encountered intersection of calculating the optimal direction a packet must take to reach its destination, allows it to avoid local maxima situations, reducing the number of packets being dropped and hence increasing the packet delivery ratio. Of course this comes as an expense to the packet delivery delay, which as it can be seen from Figure 9 is significantly higher than that imposed by the other protocols. GPCR, LOUVRE and even AODV are able to perform within the acceptable latency boundaries [29] for an application such a V-Radar, although we note the fact that queries are not propagated more than 2 roads ahead from the vehicles current position ($L = 2$). In situations that a vehicle would like to know the traffic conditions even further down the road-path ($L > 2$), the lack of data buffering may degrade the effectiveness of the aforementioned protocols. Furthermore, we observe from Figure 10 that most of the time, packets under LOUVRE require more hops from source to destination and back than GPCR and AODV. The reasoning behind this behavior, is the capacity of the LOUVRE to obtain a global view of the topology, and hence being able to route around low density areas ("voids" that cause packet drops) by introducing a few additional network hops.

V. Conclusions and Future Work

In this paper we argued that the design of VANET routing protocols should follow a realistic and complete evaluation in order to increase the possibility of identifying problems as well as implications that need to be considered and addressed to achieve optimal performance. We support our argument by evaluating the performance of three widely acknowledged

VANET routing protocols GPCR, VADD and LOUVRE in a large-scale urban environment with realistic vehicle mobility and under network traffic generated from a novel traffic query application, called V-Radar. To our knowledge this is the first performance evaluation of these three VANET-dedicated protocols. We compare the results of our evaluation approach against the results obtained by adhering to approaches typically used in the literature. Although typical scenarios such as the above and the ones used in the literature might provide indications that a particular routing protocol has an acceptable performance, they are rarely realistic. Indeed, through such a scenario we observed that carry-and-forward techniques such as the one employed by VADD perform better than greedy forward protocols in terms of packet delivery. However, by simply introducing an application such as V-Radar that requires realistic mobility and imposes delay constraints on data delivery, carry-and-forward protocols fail to perform within acceptable limits. On the other hand, greedy forwarding routing protocols such as GPCR prove that they are able satisfy low delay requirements, however they still fail in low vehicle densities due to network fragmentation. Through, the large-scale realistic scenario, we observed that both geographic and overlay routing protocols such as GPCR and LOUVRE can perform close to carry-and-forward protocols in terms of packet delivery, while still being able to satisfy the constraints of non-delay tolerant applications. From the findings in this work, one can easily acknowledge the benefits of uptaking such a thorough and realistic approach in the performance evaluation of VANET protocols. Therefore, as future work, we plan on evaluating the performance of additional routing protocols and under a complete set of realistic safety and entertainment applications.

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REFERENCES

[1] M. Sichitiu and M. Kihl, "Inter-vehicle Communication Systems: A Survey," *Communications Surveys Tutorials, IEEE*, vol. 10, no. 2, pp. 88–105, quarter 2008.

[2] G. Pallis, D. Katsaros, M. Dikaiakos, N. Loulloudes, and L. Tassiulas, "On the Structure and Evolution of Vehicular Networks," in *Modeling, Analysis Simulation of Computer and Telecommunication Systems, 2009. MASCOTS '09. IEEE International Symposium on*, Sept. 2009, pp. 1–10.

[3] J. Bernsen and D. Manivannan, "Unicast Routing Protocols for Vehicular Ad Hoc Networks: A Critical Comparison and Classification," *Pervasive and Mobile Computing*, vol. 5, no. 1, pp. 1–18, 2009.

[4] Y.-W. Lin, Y.-S. Chen, and S.-L. Lee, "Routing Protocols in Vehicular Ad Hoc Networks: A Survey and Future Perspectives," *Information Science and Engineering*, vol. 26, no. 3, pp. 913–932, 2010.

[5] "Cooperative Vehicle-Infrastructure Systems (CVIS)," http://www.cvisproject.org/ (accessed October 2012).

[6] "DRIVE C2X - Accelerate cooperative mobility," http://www.drive-c2x.eu/project (accessed October 2012).

[7] F. J. Martinez, C. K. Toh, J.-C. Cano, C. T. Calafate, and P. Manzoni, "A Survey and Comparative Study of Simulators for Vehicular Ad Hoc Networks (VANETs)," *Wireless Communications and Mobile Computing*, vol. 11, no. 7, pp. 813–828, 2011.

[8] S. Uppoor and M. Fiore, "Large-Scale Urban Vehicular Mobility for Networking Research," in *Vehicular Networking Conference (VNC), 2011 IEEE*, November 2011, p. 62.

[9] V. Naumov, R. Baumann, and T. Gross, "An Evaluation of Inter-Vehicle Ad hoc Networks Based on Realistic Vehicular Traces," in *Proceedings of the 7th ACM international symposium on Mobile ad hoc networking and computing*, ser. MobiHoc '06. New York, NY, USA: ACM, 2006, pp. 108–119.

[10] N. Wisitpongphan, F. Bai, P. Mudalige, V. Sadekar, and O. Tonguz, "Routing in sparse vehicular ad hoc wireless networks," *IEEE Journal on Selected Areas in Communications*, vol. 25, no. 8, pp. 1538–1556, 2007.

[11] C. Lochert, M. Mauve, H. Fussler, and H. Hartenstein, "Geographic Routing in City Scenarios," *SIGMOBILE Mob.Comput.Commun.Rev.*, vol. 9, no. 1, pp. 69–72, January 2005.

[12] J. Zhao and G. Cao, "VADD: Vehicle-Assisted Data Delivery in Vehicular Ad Hoc Networks," in *INFOCOM 2006. 25th IEEE International Conference on Computer Communications. Proceedings*, April 2006, pp. 1–12.

[13] K. Lee, M. Le, J. Harri, and M. Gerla, "Taking the LOUVRE Approach," *Vehicular Technology Magazine, IEEE*, vol. 4, no. 1, pp. 86 –92, march 2009.

[14] W. Chen, R. K. Guha, T. J. Kwon, J. Lee, and Y.-Y. Hsu, "A Survey and Challenges in Routing and Data Dissemination in Vehicular Ad Hoc Networks," *Wireless Communincations and Mobile Computing*, vol. 11, no. 7, pp. 787–795, jul 2011.

[15] V. Naumov and T. Gross, "Connectivity-Aware Routing (CAR) in Vehicular Ad-hoc Networks," in *INFOCOM 2007. 26th IEEE International Conference on Computer Communications. IEEE*, may 2007, pp. 1919 –1927.

[16] A. Skordylis and N. Trigoni, "Delay-bounded Routing in Vehicular Ad Hoc Networks," in *Proceedings of the 9th ACM international symposium on Mobile ad hoc networking and computing*, ser. MobiHoc '08. New York, NY, USA: ACM, 2008, pp. 341–350.

[17] Y. Ding and L. Xiao, "SADV: Static-Node-Assisted Adaptive Data Dissemination in Vehicular Networks," *Vehicular Technology, IEEE Transactions on*, vol. 59, no. 5, p. 2445, June 2010.

[18] "i-Tetris - An Integrated Wireless and Traffic Platform for Real-Time Road Traffic Management Solutions," http://ict-itetris.eu (accessed October 2012).

[19] "U.S. Census Bureau, TIGER system," http://www.census.gov/geo/www/tiger/.

[20] "The TAPAS-Cologne Project," http://sourceforge.net/apps/mediawiki/sumo/index.php?title=Data/Scenarios/TAPASCologne (accessed October 2012).

[21] "Simulation of Urban Mobility - SUMO," http://sumo.sourceforge.net/.

[22] N. Loulloudes, G. Pallis, and M. D. Dikaiakos, "Caching Dynamic Information in Vehicular Ad Hoc Networks," in *Proceedings of the 16th international Euro-Par conference on Parallel processing: Part II*, ser. Euro-Par'10. Berlin, Heidelberg: Springer-Verlag, 2010, pp. 516–527.

[23] M. Dikaiakos, A. Florides, T. Nadeem, and L. Iftode, "Location-Aware Services over Vehicular Ad-Hoc Networks using Car-to-Car Communication," *Selected Areas in Communications, IEEE Journal on*, vol. 25, no. 8, pp. 1590 –1602, oct. 2007.

[24] "The Network Simulator (ns-3)," http://www.isi.edu/nsnam/ns/.

[25] C. Perkins, E. Belding-Royer, and S. Das, "Ad hoc On-Demand Distance Vector (AODV) Routing," United States, 2003.

[26] Connect & Drive project (HTASD08002) , "C&D WP-1 requirements document," Tech. Rep., April 2009.

[27] IEEE, "Draft Amendment to Standard for Information Technology-Telecommunications and Information Exchange between Systems-Local and Metropolitan Area Networks-Specific Requirements – Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications-Amendment 7: Wireless Access in Vehicular Environment," *P802.11p/D3.0*, 2007.

[28] J. Y. Yen, "Finding the K Shortest Loopless Paths in a Network," *Management Science*, vol. 17, no. 11, pp. 712–716, 1971.

[29] V. S. C. Project, "Task 3 Final Report: Identify Intelligent Vehicle Safety Applications," U.S. Dept. of Transport - National Highway Traffic Safety Administration, Tech. Rep., March 2005.