Evaluation of Routing Protocols for Vehicular Ad Hoc Networks in Typical Road Traffic Scenarios

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***Abstract*— Vehicular multi-hop ad hoc networks (VANETs) enable the exchange of information between vehicles without any fixed infrastructure. The application range of such networks may cover safety related applications like the warning of drivers about accidents or congestions as well as Internet access e.g. via gateways along the road. The varying conditions in VANETs introduce high requirements on the routing protocols being used. Thus, we developed a realistic freeway mobility model and evaluated the performance of AODV, DSR, FSR and TORA in typical freeway traffic scenarios on the basis network simulations. The results show that AODV performs best in most of the simulated traffic situations, followed by FSR and DSR, while TORA is inapplicable for VANETs.**

I. INTRODUCTION

The exchange of information between communicating vehicles without any fixed infrastructure like access points or base stations is an intensive field of research. Upcoming technologies like FleetNet [1] are based on multi-hop ad hoc networks using Dedicated Short Range Communication for vehicular communications systems. Since each network node acts as wireless station and mobile router at the same time, distant vehicles can communicate with each other using intermediate vehicles for packet forwarding. The application range of such networks may cover safety related applications like the warning of drivers about accidents or congestions. For these purposes, not only vehicles, but also traffic signs may take part in the VANET. Moreover, vehicles may also be provided with Internet access via the ad hoc network using e.g. gateways installed along the roadside [2]. The routing of data packets through the VANET is very complex since the network topology and the communication conditions may vary heavily. Several factors like the type of the road, daytime, weather, traffic density and even the driver himself affect the movements of vehicles on a road. Hence, the network topology changes frequently, and the routing protocol used has to adapt itself to theses changes continuously. Up to now, most general work on the performance of routing protocols in MANETs [3], [4] considers only a quite small number of nodes and/or a low mobility as well as simple movement patterns. Thus, one of our goals is to model more realistic movement patterns for the simulations that reflect the movement of vehicles in typical traffic situations.

Current routing protocols can be categorized into topology-based and location-based protocols. In our paper, we focus on topology-based routing protocols since these do without any location services for determining the nodes' geographic positions. We chose four protocols to be compared: Ad Hoc On Demand Distance Vector (AODV) [5], Dynamic Source Routing (DSR) [6], Fisheye State Routing (FSR) [7] and Temporally-Ordered Routing Algorithm (TORA) [8]. AODV, DSR and TORA belong to the class of reactive (on-demand) routing protocols that discover routes through the network when they are needed, while proactive routing protocols like FSR continuously maintain routes to all possible destinations.

The remaining paper is organized as follows: Section II presents the mobility model used. Afterwards, the scenario characteristics and simulation results are discussed in Section III. The paper closes with a conclusion in Section IV.

II. FREEWAY MOBILITY MODEL

Choosing a specific mobility model clearly affects the simulation results [9]. Thus, simple models like the Random Waypoint Model are completely inapplicable for simulating VANETs. For that reason, we developed a mobility model that reflects the movement of vehicles on a freeway realistically. However, since freeway traffic is very heterogeneous, several simplifications are needed. In our freeway mobility model, we assume that all vehicles are equal and no distinction between e.g. cars or trucks is made. Moreover, they are supposed to be points on a straight line that represents a lane of the freeway. The freeway mobility model is based on two main approaches: On the one hand, the speed of a vehicle is adapted according to the *Intelligent-Driver Model (IDM)* [10]. IDM is a microscopic traffic model that emulates realistic vehicular movements.

According to (1), it determines the acceleration of a vehicle n at a distinct point in time on the basis of its current speed v_n, the net distance s_n to the leading vehicle $n-1$, and the

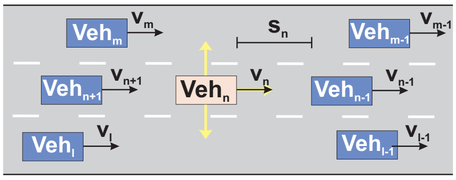

Fig. 1. Influencing variables on IDM an MOBIL

approaching rate $\Delta v_n = v_n - v_{n-1}$ to this vehicle as shown in Fig. 1.

$$\dot{v}_n^{IDM}(v_n, s_n, \Delta v_n) = a_n \cdot \left[1 - \left(\frac{v_n}{v_{\text{des}}^{(n)}} \right)^{\delta} - \left(\frac{s^*\left(v_n, \Delta v_n\right)}{s_n} \right)^2 \right] \quad (1)$$

The first part of the equation ($a_n[1-(v_n/v_{\text{des}}^{(n)})^{\delta}]$) describes the vehicle's acceleration on an empty road, depending on its maximum acceleration a_n, the driver's desired speed v_{des}, and an acceleration exponent δ. The remaining term represents a brake retardation. It is affected by a desired distance s^* to the leading vehicle, which is determined according to (2).

$$s^*(v_n, \Delta v_n) = s_{\text{con}}^{(n)} + T v_n + \frac{v_n \Delta v_n}{2 \cdot \sqrt{a_n b_n}} \quad (2)$$

s^* considers a congestion distance $s_{\text{con}}^{(n)}$ between stopped vehicles and a safe time headway T. The rear term describes the vehicle's braking effect when approaching to other vehicles, whereas b_n is the vehicle's comfortable deceleration.

Further important characteristics of freeway traffic are frequent overtaking maneuvers of vehicles. The accurate emulation of lane-changes is very complex, but for our purposes we need a mechanism that manages with a clear set of parameters. Therefore, we use the lane-change strategy *MOBIL* (Minimizing Overall Breaking Induced by Lane-Changes) [10]. MOBIL induces a vehicle to change its current lane if this lane-change is advantageous for the local traffic situation of the vehicle and its neighbors on the basis of the vehicles' IDM accelerations.

MOBIL uses two criteria to come to a decision. The *safety criterion* ensures that after a lane-change the vehicle coming from behind does not need to slam on the breaks by limiting the maximum brake retrardation to b_{save}. The *incentive criterion* determines whether a lane-change is necessary. It is based on the current and virtual de-/accelerations of all vehicles in the local traffic situation as depicted in Fig. 1. For a lane-change of vehicle n from the middle to the left lane, the criterion is given by:

$$a_{n(m-1)} + p\big(a_{mn} + a_{(n+1)(n-1)}\big) > a_{n(n-1)} + p\big(a_{(n+1)n} + a_{m(m-1)}\big) + \gamma \quad (3)$$

(3) also considers a politeness factor p that reflects the willingness of a driver to change the lane, and a threshold γ in order to avoid ping-pong effects. The incentive criterion is met if the acceleration of the examined vehicle and the weighted accelerations of the neighbored vehicles after the lane-change are greater than the overall accelerations before the lane-change and the threshold. The whole set of constant parameters used for IDM and MOBIL is summarized in Table I.

We implemented the freeway mobility model into a movement scenario generator that is able to create various movement scenarios with different characteristics.

TABLE I

CONSTANT PARAMETERS OF IDM AND MOBIL

Param.	Description	Value
a	Maximum acceleration	$1.2\,\text{m/s}^2$
b	Comfortable deceleration	$1.5\,\text{m/s}^2$
δ	Acceleration Exponent	4
s_{con}	Minimum congestion distance	$2\,\text{m}$
T	Safe time headway	$1.4\,\text{s}$
b_{save}	Limiting value of brake retardation	$0.5\,\text{m/s}^2$
p	Politeness factor	$\in [0, 1]$
γ	Lane-change threshold	$0.8\,\text{m/s}^2$

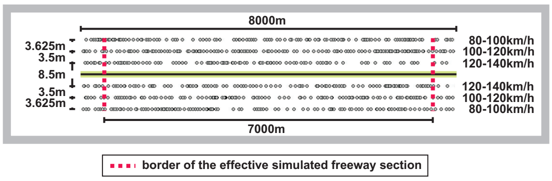

Fig. 2. Characteristics of the freeway scenario

III. EVALUATION

For evaluating the performance of the routing protocols mentioned above, we used the open source and freely available network simulator ns-2 [11] in its version 2.27. The simulations are done on the packet level, which enables a detailed analysis of the results.

A. Scenario Characteristics

In this paper, we consider two freeway traffic scenarios: a clear freeway and a freeway that is congested in one direction. In both cases, vehicles are able to communicate with each other using IEEE 802.11. The radio transmission range is assumed to be 100 m. Since vehicles on clear freeways drive at high speeds, we have to simulate a quite large section of a freeway. Thus, the length is assumed to be 8 km. ns-2 requires that vehicles leaving the simulated freeway section at one end have to reappear at the beginning of any other lane. Hence, we have to ignore the communication of vehicles on the first and last 500 m of the section to avoid undesirable effects. Due to these guard distances, vehicles can e.g determine their new neighbors when appearing at the beginning of a freeway lane. The freeway's cross-section is modeled according to German regulations. Our freeway mobility model assumes that all vehicles determine a desired speed when entering the simulated freeway section. The speeds depend on the the separate lanes and were chosen between 80 km/h and 140 km/h according to results in [12]. Fig. 2 shows an exemplary movement pattern and the characteristics of the clear freeway scenario.

The congestion scenario differs from the previous scenario in the way that vehicles in one direction of the freeway do not move. The traffic density on congested lanes reaches a constant value of about 140 veh/km [12]. For this reason, we reduced the length of the simulated freeway section to 5 km in order to have a comparable number of nodes in both scenarios.

TABLE II

PARAM. FOR CLEAR FREEWAY

density p. lane [veh/km]	#nodes	max. #conn.
2	96	48
5	240	120
10	480	240
15	720	360
20	960	480
25	1200	600

TABLE III

PARAM. FOR CONGESTION

penetr. [%]	#nodes	max. #conn.
0.05	123	62
0.1	247	124
0.2	495	248
0.3	742	371
0.4	990	495
0.5	1237	619

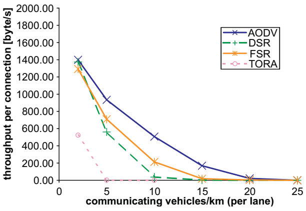

Fig. 3. TCP throughput (clear Fw)

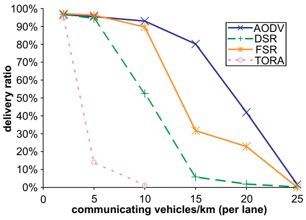

Fig. 4. Delivery ratio (clear Fw)

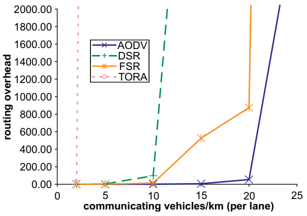

Fig. 5. Rt. overhead (clear Fw)

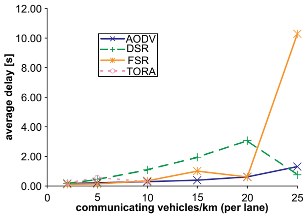

Fig. 6. Avg. delay (clear Fw)

Our freeway mobility scenario also considers different traffic densities. The traffic density on a freeway is colloquially described as high when it reaches a value of at least 30 veh/km (per lane) [12]. Typically, not all of these vehicles will participate in the ad hoc network, e.g. if they are not equipped with the necessary hardware. To bring the huge simulation efforts down to an acceptable level, only communicating vehicles are considered in the simulation, while non-communicating vehicles are neglected. Traffic densities between two and 25 communicating veh/km (per lane) are modeled in our scenarios. In the congestion scenario, we varied the penetration of communicating vehicles since the traffic density on each congested lane is constantly 140 veh/km. We assumed an average traffic density of 25 veh/km on the clear lanes and simulated penetrations between 5 % and 50 %. The duration of each simulation run is limited to four minutes. Vehicles driving on a freeway may not only communicate with other vehicles driving in the same direction, but also with vehicles in the contraflow traffic. This affects the communication performance since the difference in speed of both communication partners is very high. Hence, the communication path from the traffic source to the destination may change more frequently than in the other case. In our measurements, we assume that 80 % of the connections are established between vehicles driving in the same direction. Tables II and III summarize the important parameters of both scenarios.

B. *Simulation Results*

Our evaluation is based on four performance measures [13]: end-to-end throughput, packet delivery ratio, routing overhead and average end-to-end delay. Fig. 3 shows the average TCP throughput per connection against the traffic density (per lane) in the clear freeway scenario. The graphs of all routing protocols show a negative exponential progression, which can be explained by the increasing number of neighbors within a vehicle's direct communication range (2.4 neighbors at 2 veh/km vs. 30 neighbors at 25 veh/km). Throughout all simulated traffic densities, AODV was able to provide the highest throughput (up to 1399.28 byte/s) of all protocols, followed by FSR. DSR's throughput decreases very fast up to a traffic density of 10 veh/km (from 1373.70 byte/s to 37.56 byte/s). Finally, we can see that from a traffic density of 5 veh/km on, TORA only achieves an extremely low throughput. Unfortunately, we were only able to simulate TORA up to a traffic density of 10 veh/km due to the enormous memory requirements. However, we can expect that the results at higher densities are still lower.

The delivery ratio of TCP packets shown in Fig. 4 emphasizes these results. We can see that at a traffic density of 2 veh/km all protocols are able to deliver more than 94 % of the data packets sent, while this share plunges down to less than 2 % at a traffic density of 25 veh/km.

The protocols' normalized routing overhead is shown in Fig. 5. It represents the ratio of routing data sent to user data delivered to the destinations. Especially at higher traffic densities all protocols cause very high overhead. This results from the low data throughput at the specific traffic densities as well as the large number of network participants and the high mobility of the vehicles. Assuming a traffic density of 2 veh/km, the overhead of AODV, FSR and DSR is lower than one, while TORA already sends 29.15-times more routing data than user data is delivered. At a traffic density of 5 veh/km, TORA's overhead already jumps up to 33350.67, while especially AODV and FSR manage with clearly less overhead.

Fig. 6 shows the average end-to-end delay of delivered data packets. Assuming a traffic density of 25 veh/km, FSR was able to deliver packets fastest (0.12 s). However, AODV (0.16 s), DSR (0.18 s) and TORA (0.21 s) were also able to deliver packets very fast. DSR's delay increases up to 3.06 s at a traffic density of 20 veh/km. The decrease of the delay at a traffic density of 25 veh/km can be explained with the fact that only very few data packets were delivered in this case. Thus, these results have to be taken with a pinch of salt. Conspicuously, FSR's delay at a traffic density of 25 veh/km increases to 10.28 s. This can be explained by the huge link-state updates that are exchanged by the nodes in this case. Thus, the wireless channel is allocated for transmitting these updates for a very long period of time, especially because routing messages have a higher priority in the node's interface

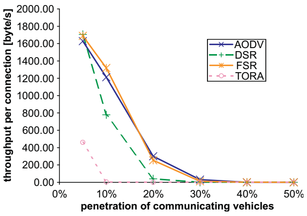

Fig. 7. TCP throughput (Cong.)

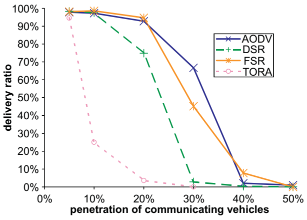

Fig. 8. Delivery ratio (Cong.)

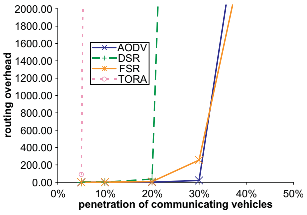

Fig. 9. Rt. overhead (Cong.)

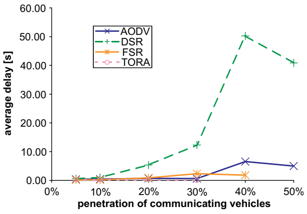

Fig. 10. Avg. delay (Cong.)

queue.

Fig. 7 to 10 show the appropriate simulation results of the congestion scenario. Again, AODV and FSR clearly outperform the other protocols.

In summary it may be said that AODV is characterized by a comparatively high throughput and low routing overhead in nearly all modeled situations. Here, AODV presses home its advantage of exchanging only small routing messages. ADOV was able to cope best with the fast changing network topology and the high relative speeds of the vehicles. Its average end-to-end delay was quite low throughout the road traffic scenarios. FSR also reaches quite good results. However, it takes only limited advantage of its mechanisms for reducing the size of link-state updates since the vehicles' mobility on the freeway is very high and thus vehicles cover large distances during an update interval. FSR suffers from quite long average end-to-end delays at very high traffic densities. Besides the problem that the number of delivered data packets decreases with the density of communicating vehicles and thus fewer packets account for the determination of the delay, also the exchange of many large routing updates may delay the transmission of data packets. DSR suffers from a high routing overhead and long transmission delays. Since routes change frequently, high efforts are needed to maintain source routes through the network. Thus, DSR is not well suited for VANETs. Finally, the simulations showed that TORA is completely inapplicable for VANETs. Already at lower traffic densities, its throughput converges to zero and its routing overhead jumps up. Moreover, it also suffers from high mobility in VANET environments since the network's graph representation has to be updated permanently.

IV. CONCLUSIONS

Vehicular multi-hop ad hoc networks are a key technology for the future development of vehicular communications systems. However, the routing of packets through the VANET is very complex due to the high mobility of the vehicles and the fast changing network topologies. In this paper, we compare the performance of the routing protocols AODV, DSR, FSR and TORA in such VANET environments on the basis of network simulations. We therefore developed realistic models for generating typical vehicular movement patterns. Our evaluation showed the strengths and weaknesses of proactive and reactive ad hoc routing protocols in VANET scenarios. An important observation was that the examined routing protocols showed highly heterogeneous performance results. In summary, AODV achieved the best performance throughout the traffic scenarios, followed by FSR. AODV causes only little overhead compared to the other protocols in most of the simulated scenarios. FSR suffers from a high routing overhead at higher traffic densities. Another problem of FSR was the long initialization phase while link-state information is spread through the network for the first time. DSR also suffers from a high routing overhead and delay. Since the topology of the network changes frequently, the source route information is only valid for a limited period of time. Finally, we observed that TORA is inapplicable for VANET environments.

Future work will include the simulation of additional typical road traffic scenarios in order to determine potentials for optimizing routing protocols in VANETs. Moreover, we will analyze the effects of integrating Internet gateways and traffic signs into the VANET in order to develop cooperative applications for improving road safety and driver assistance.

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