Reliable Message Forwarding in VANETs for Delay-Sensitive Applications

Karsten Roscher, Gerhard Maierbacher
Fraunhofer ESK
Munich, Germany
Email: {karsten.roscher,gerhard.maierbacher}@esk.fraunhofer.de

Abstract—Multi-hop forwarding in VANETs remains a challenging task. Existing protocols either focus on high packet delivery ratios or low latencies. In this paper, we propose Low-Delay Forwarding with Multiple Candidates (LDMC), a novel geographic routing approach using a combination of sender-based forwarder selection and receiver-based coordination of multiple contenders. Candidates are rated based on a combination of position and relative speed information. Contention among forwarders is realized with priority-dependent timers. Our evaluation shows substantial improvement of the forwarding delay while maintaining high packet delivery ratios comparable to contention-based algorithms for different scenarios. Hence, the proposed concept is well suited for delay-sensitive applications like cooperative positioning or coordinated driving.

I. INTRODUCTION

Vehicular ad-hoc networks (VANETs) are of high interest to enable future advanced driver assistance systems and pave the way for coordinated automated driving. Network layer protocols with multi-hop support can increase the communication range and allow information exchange between stations without a direct wireless link, e.g. around buildings or other obstacles. However, VANETs are highly dynamic wireless networks with constantly changing topologies. Thus, discovery and maintenance of suitable forwarding paths remains a challenging task.

The class of geographic routing protocols is a promising candidate for multi-hop communication in VANETs [1]. Its stateless nature avoids the increased overhead for rapidly changing topologies caused by path discovery and maintenance. Furthermore, the widespread deployment of positioning systems like GPS in vehicles eases the implementation of position-based algorithms. Geographic routing protocols can be roughly divided into two classes depending on the strategy for selection of the next hop in the forwarding path: sender-based and receiver-based [2].

In sender-based approaches, a node that intends to forward a message explicitly selects the next hop among its direct neighbors. Most selection metrics require regular exchange of status information, i.e. through periodic beacons. Packets are transmitted to the selected node using a unicast transmission on the wireless medium. Sender-based protocols generally provide low end-to-end delay. However, they suffer from decreased reliability due to high error rates on the wireless channel caused by multi-path fading, shadowing and collisions on the shared medium.

In receiver-based (or opportunistic) protocols, the forwarding decision is shifted towards the potential next hop candidates. A packet is forwarded to all direct neighbors using broadcast mode on the wireless medium. Upon reception, each node checks if it is a potential candidate for forwarding, e.g. it is closer to the destination than the transmitter of the packet. Afterwards, all candidates contend for packet forwarding using a timer-based coordination function. Each node applies a delay before the packet is retransmitted. If a retransmission of the same packet is overheard during the waiting period, the associated timer is canceled and the packet is discarded. Receiver-based protocols offer an increased reliability because they leverage all potential forwarders in a region. Progress is made as long as at least one candidate receives the packet. This is especially suitable for scenarios with higher network densities. However, the increase in reliability also leads to increased end-to-end delays since each hop adds additional waiting times. Thus, a key factor in the design of such protocols is the selection of a suitable delay function to ensure a sufficient separation of the forwarders in the time domain while keeping overall waiting times as short as possible.

In this paper we introduce a new routing protocol called Low-Delay Forwarding with Multiple Candidates (LDMC) which exploits the advantages of sender-based selection algorithms in terms of low latency together with the increased reliability of opportunistic protocols:

- Direct neighbors are ranked according to a combined metric based on position and relative speed to increase the progress per hop while avoiding short-lived links due to vehicles moving in opposite directions.
- Instead of choosing a single next hop, an ordered set of candidates is selected. The size of the set determines the balance between reliability and protocol overhead.
- The individual forwarding delay is based on the position in the candidate set. Additional waiting time can be completely avoided if the best entry can forward the packet. Furthermore, the applied waiting time for the other entries does not depend on the distribution of nodes or other environmental factors.

Simulation results show that the achieved packet delivery ratios are comparable to other opportunistic protocols while significantly reducing the end-to-end delay.

The remainder of this work is organized as follows: Section
II provides a review of related work. Section III describes our forwarding approach which is evaluated in detail in Section IV. Finally, a summary of the results and an outlook on future work are given in Section V.

II. RELATED WORK

The basis for most sender-based geographic routing protocols is Greedy Perimeter Stateless Routing (GPSR)\cite{3} which uses a greedy approach to maximize the distance covered with each hop in cooperation with a fall-back strategy to route around a local maximum (dead end). GPSR without perimeter mode is also included in the relevant ETSI ITS standard as Greedy Forwarding\cite{4}. Like all sender-based protocols, GPSR depends on up-to-date information from neighbors provided via periodic beacon messages. However, a strategy based on maximizing the distance gain per hop often leads to a selection of next hops close to the edge of the transmission range with links suffering from a high error probability. Therefore, several authors proposed to include speed and heading into the selection process to either predict if a neighbor is already out of range\cite{5} or to improve the position information between beacons via estimation\cite{6}. Other sender-based protocols focus on the special role of vehicles close to intersections in urban scenarios where buildings and other obstacles allow communication only along the roads. GPCR\cite{7}, GpsrJ+\cite{8} and GROOV\cite{9} apply heuristics to detect junctions and prefer the selection of nodes close to it. But even though a better selection of the next hop increases end-to-end reliability overall sender-based approaches still suffer from the dependency on a single node that might fail or cannot be reached due to changes in the wireless environment.

Therefore, opportunistic routing was originally investigated for wireless mesh networks to provide highly reliable transmissions by leveraging multiple forwarders in each step. ExOR\cite{10} and SOAR\cite{11} are protocols where a list of neighbors that could act as a relay is compiled by the sender. This list is ordered by priority and attached to the transmitted packet. ExOR and SOAR rank all potential forwarders by their estimated cost of delivery to the destination. In addition, SOAR restricts the candidate set to nodes close to a direct path to the destination. This avoids duplicate transmissions by diverging paths. However, the chosen ranking metric requires knowledge of all inter-node loss rates which is not applicable to highly dynamic VANETs.

Contention-Based Forwarding (CBF)\cite{12},\cite{4} and BLR\cite{13} apply opportunistic principles to geographic routing. Packets are broadcast without any restrictions. Each receiver that is closer to the destination than its predecessor is a forwarding candidate. The waiting for each candidate is determined locally based on its individual progress towards the destination: less progress leads to longer waiting times. This approach ensures fewer hops in dense scenarios but leads to increased per-hop delay if no neighbors with sufficient progress are available. Similar to sender-based approaches, intersections have received increased attention for receiver-based protocols as well. TOpology-assist geo-opportunistic routing (TO-GO)\cite{14} limits the candidate set to nodes close to a junction. The delay for each candidate depends on the distance to a target node selected by the sender. Similar to CBF and BLR, an increase in per-hop delay can be observed especially for networks with low to medium density or uneven node distribution.

III. LOW-DELAY FORWARDING WITH MULTIPLE CANDIDATES

The main idea of our LDMC approach is to combine a sender-based selection of forwarding candidates with a decentralized coordination among them. Each packet is handled individually allowing to quickly react to changes in the topology. Nodes have to know their own geographic position. Furthermore, we assume that the position of the destination node is known by the source when the packet is sent. This can be either achieved through information contained in already received packets or via an additional Location Service that is out of the scope of this paper. In addition, we assume knowledge about direct neighbors through periodic beacons that contain a station identifier as well as the current position and a velocity vector.

In each forwarding step, the current node specifies the Forwarder List in priority order based on a specific Rating Metric. The list is added to the header of the packet before it is transmitted via broadcast to all neighbors. Each receiving node first checks if it is the destination of the packet. If so, it forwards the packet to the higher layers and stops further processing. If the receiver is not the destination the Forwarder Coordination process is initiated.

A. Forwarder List

The forwarder list \( F = \{f_1, \ldots, f_i\} \) is a subset of all direct neighbors closer to the destination than the current node ordered by a specific Rating Metric. Depending on the size of the list, three cases can be identified:

- \( |F| = 1 \): A list with exactly one entry is similar to sender-based routing protocols with explicit selection of a next hop.
- \( |F| > 1 \): A list with multiple entries allows for receiver-based contention among the candidates.
- \( |F| = \emptyset \): The list is empty. The packet can either be buffered (store-and-carry forwarding) or it is broadcast with an empty list falling back to simple CBF behavior on the receiver side.

A configuration parameter \( i_{max} \) determines the maximum size of the list. If the current neighborhood provides more direct neighbors than \( i_{max} \) only the first \( i_{max} \) entries are used for the next hop. Fewer potential forwarders reduce the overhead caused by adding more entries to the packet header. On the other hand, more candidates can increase reliability through additional relay nodes.

B. Rating Metrics

Rating metrics evaluate neighboring nodes with respect to their suitability as potential forwarders for a packet. In LDMC
we use a combination of a distance-based metric, aiming to increase the progress with each hop, with a metric based on relative velocity between the current node and the potential candidate. The latter is intended to avoid the selection of nodes that move away with high speed and thus might already be out of communication range.

In order to prefer nodes closer to the destination, we calculate the distance metric as follows:

\[
    r_{dist}(i) = 1 - \frac{|pos(i) - pos(d)|}{|pos(c) - pos(d)|} \tag{1}
\]

where \( i \) is the node to evaluate, \( c \) is the current node, \( d \) is the destination node and \( pos(a) \) is the position of node \( a \). Note that this definition, in contrast to the distance-based timers in CBF [12] or BLR [13], does not require a fixed maximum transmission range parameter that has to be predefined but can not be determined reliably for the varying propagation environments encountered in VANETs.

Candidates moving away from the current node may have left the communication range since the last received beacon. Thus, we derive a rating metric based on a logistic function that uses the relative velocity to prefer neighbors moving towards the current node \( c \) as follows:

\[
    r_{vel}(i) = \frac{1}{1 + e^{-k(v_{rel}(c,i) - v_0)}} \tag{2}
\]

where \( v_{rel}(c,i) \) is the change in distance between \( c \) and \( i \) over time, i.e. \( v_{rel} \) is positive if \( c \) and \( i \) move away from each other and negative if they are moving towards each other. \( k \) controls the steepness of the curve and \( v_0 \) is the point where the metric value is 0.5. Fig. 1 illustrates the function for different settings.

A weighted sum of the individual metrics, similar to the approach in TLG [15], is proposed to balance the different optimization goals:

\[
    r = \omega_{dist} \cdot r_{dist} + \omega_{vel} \cdot r_{vel} \tag{3}
\]

where \( \omega_{dist} \) and \( \omega_{vel} \) are the individual weights for the distance and velocity metric respectively.

C. Forwarder Coordination

After the successful reception of a packet, all nodes for which the local identifier is part of the Forwarder List of the received packet take part in the contention for rebroadcasting. Decentralized coordination is realized through different retransmission delays based on the position \( p_c \) of the node’s identifier in the list, starting with 0 for the first entry:

\[
    t_{wait} = p_c \cdot t_f \tag{4}
\]

where \( t_f \) is a configuration parameter defining the time difference between two consecutive list entries. It should be large enough to allow a sufficient separation of channel access attempts to avoid collisions. However, larger values will also lead to increased end-to-end delay. Similar to other opportunistic approaches, a node cancels its timer and drops the associated packet if it overhears another node forwarding the packet during its waiting time.

The coordination process can be extended by adding the basic CBF procedure for all nodes that are not in the forwarder list. This will improve reliability by including neighbors, the previous forwarder was not yet aware of or that moved into a better position since their last update. It will only be triggered, if all nodes in the list fail to receive the packet. To avoid interference with the actual LDUC protocol, the waiting time implied by the forwarder list is added to the CBF-based timeout:

\[
    t_{wait, CBF} = |F| \cdot t_f + t_{CBF} \tag{5}
\]

where \( |F| \) is the size of the forwarder list and \( t_{CBF} \) is the timeout duration calculated with the CBF function in [4].

IV. Evaluation

To evaluate the performance of the proposed approach it is compared to Greedy Forwarding and Contention-Based Forwarding (CBF) as defined in ETSI ITS GeoNetworking [4]. The simulation environment consists of the network simulator ns-3 [16], the traffic simulator SUMO [17] and the ETSI ITS protocol stack implemented by the ezCar2X framework [18], [19]. Table I summarizes the parameters used for the simulation.

A. Freeway Scenario

We selected a 4km highway with 3 lanes in each direction to evaluate the line forwarding properties of our approach. Vehicles are moving along the road with different speeds between 80 and 130 km/h. Departure times are randomized. On average, around 270 vehicles are active in the simulation. For each packet, a random pair of nodes is chosen as source and destination. However, sufficient space on each end of the highway is excluded to avoid edge effects.

Fig. 2 shows the cumulative delay distribution for the described scenario where LDUC considers only forwarders provided in the forwarder list. LDUC+CBF adds CBF for nodes not in the list. All approaches work well with minimal delay if the destination can be reached directly, i.e. no multi-hop forwarding is involved. However, the Greedy protocol
TABLE I
SIMULATION PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>802.11p</td>
</tr>
<tr>
<td>Tx Power, Tx Rate</td>
<td>20 dBm, 6 Mbps</td>
</tr>
<tr>
<td>Propagation Model (Freeway)</td>
<td>Nakagami [20]</td>
</tr>
<tr>
<td>Propagation Model (Grid)</td>
<td>Chen et al. [21] with [22]</td>
</tr>
<tr>
<td>Packet Size, Packet Interval</td>
<td>300 Bytes, 0.1s</td>
</tr>
<tr>
<td>Beacon Interval</td>
<td>1.0s ... 1.25s</td>
</tr>
<tr>
<td>Neighbor Timeout</td>
<td>20s [4]</td>
</tr>
<tr>
<td>$t_{\text{max}}, t_f$</td>
<td>10, 1ms</td>
</tr>
<tr>
<td>$k_v$, $v_0$</td>
<td>-1.0, 5.0</td>
</tr>
<tr>
<td>$w_{\text{dist}}, w_{\text{vel}}$</td>
<td>0.1, 1.0</td>
</tr>
<tr>
<td>Simulation Runs</td>
<td>32</td>
</tr>
<tr>
<td>Duration per Run</td>
<td>1000s</td>
</tr>
</tbody>
</table>

Fig. 2. Cumulative Delay Distribution for the Freeway Scenario

regularly fails to deliver packets beyond the first hop due to stale neighbor information, caused by the long entry timeout specified in the standard [4], combined with high relative speeds of the vehicles moving in opposite directions. On the other hand, CBF can provide high reliability (up to 98%) at the cost of longer delays. With CBF only 55% of the packets are received within 100ms. Both LDMC variants successfully delivered more than 90% of the packets in the same time frame. LDMC+CBF provides a slight benefit over LDMC for packets arriving later than 100ms coming close to the CBF performance if no deadline is considered.

B. Manhattan Grid Scenario

The grid scenario consists of a road network with single lane streets, block sizes of 360x100 meters, and 4 blocks in each direction. Buildings occupy the space in between with a distance of 15m to the road center. Vehicles take random trips within the network with a maximum speed of 50 km/h. On average, 250 vehicles are active on the road. Similar to the freeway scenario, a random pair of nodes is chosen as source and destination for each packet.

Fig. 3 shows the cumulative delay distribution for the grid. Similar to the freeway scenario, Greedy forwarding fails to deliver packets beyond the first hop. Additional relay nodes provided by LDMC lead to a significant increase in reliability without adding notable delay. However, LDMC without CBF delivers only 50% of the packets but most of them with a latency of less than 20ms. With CBF and LDMC+CBF on the other hand, achievable latencies are distributed over a larger interval with packets being received even after 700ms. Overall, both approaches reach packet delivery ratios up to 90% percent if time is not an issue. Depending on the specific latency requirements of the application, LDMC+CBF performs significantly better than all other approaches in the window of 100 to 500ms. If the application strictly requires packet delivery within 100ms, LDMC outperforms both standardized protocols by a factor of 4 to 5 with respect to the packets received in time.

C. Overhead

Additional overhead compared to Greedy and CBF is introduces by LDMC through an increased packet size due to the included forwarder list of up to 60 Bytes. Furthermore, redundant packet transmissions by candidates not overhearing each other can increase the load on the wireless channel. To compare the protocols we measured the times a packet was handed to the MAC layer while traveling from source to destination as well as the Channel Busy Ratio (CBR) at a defined location. In both scenarios, several probes where deployed in the simulation. In this paper, we consider the measurements from the probe located at the center of the topology. However, other probes showed similar trends.

Table II shows the average values for the number of forwarding attempts per packet aggregated over the entire path. Greedy’s attempts barely exceed 1 which matches the observation that communication beyond 1-hop range is almost impossible. CBF and LDMC+CBF perform similarly but both require many transmissions to ensure high reliability. Especially in the freeway scenario basic LDMC is a
viable alternative with only half of the forwarding operations but only a few percent less packets received. However, the fourfold improvement for the grid scenario is a result of the decreased packet delivery ratio with LDMP compared to CBF or LDMP+CBF.

The CBR values provided in Table III include the additional overhead from increased header sizes as well as the static load by periodic beacons. The main observations match the evaluation of forwarding attempts. However, even though LDMP+CBF forwards packets slightly less often, the CBR values are a little higher than plain CBF due to larger packets. Again, basic LDMP performs very efficiently in the freewayscenario. The fact that it causes even less CBR in the grid scenario than Greedy forwarding can be attributed to the different transmission schemes on the MAC layer. Greedy utilizes MAC unicast leading to up to 7 retransmission of a single packet in case of failures but those retransmissions are not included in the provided forwarding count. LDMP on the other hand uses broadcast on layer 2 which is sent only once.

V. Conclusion

In this paper we proposed LDMP, a geographic routing protocol for applications with strict latency requirements. Multiple forwarding candidates are prioritized by the sender and enclosed in each packet. Our simulations showed that decentralized coordination of contenders based on priority significantly decreases forwarding delays and decouples waiting times from the geographic distribution of potential forwarders. Achievable latencies strongly depend on the selection of good candidates for the next hop. To improve the performance in grid-like scenarios, the proposed protocol can be extended with a metric to prefer nodes close to intersections [14]. In addition, evaluation should be extended to more realistic scenarios and optimization of the metric weights as well as other parameters needs to be investigated.

REFERENCES


TABLE II

<table>
<thead>
<tr>
<th>Average Times Forwarded</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greedy</td>
</tr>
<tr>
<td>Freeway</td>
</tr>
<tr>
<td>Grid</td>
</tr>
</tbody>
</table>

TABLE III

<table>
<thead>
<tr>
<th>Channel Busy Ratio [6]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greedy</td>
</tr>
<tr>
<td>Freeway</td>
</tr>
<tr>
<td>Grid</td>
</tr>
</tbody>
</table>