Low-Delay Forwarding with Multiple Candidates for VANETs Using Multi-Criteria Decision Making

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Abstract—**Vehicular ad hoc networks (VANETs) are envisioned to support driver assistance and automated driving posing strict requirements on communication reliability and delay. To support these applications, we propose Low Delay Forwarding with Multiple Candidates (LDMC), a geographic routing approach combining the advantages of sender-based control and opportunistic forwarding. Candidates are ranked based on position, time since the last status update and neighborhood information using multi-criteria decision making. Priority-dependent timers reduce the contention among forwarders. Our evaluation for freeway and grid scenarios shows substantial improvement over existing protocols for real-time applications requiring 100 ms or less end-to-end delay.**

I. INTRODUCTION

Wireless communication among vehicles is intended to increase the perception range of advanced driver assistance systems beyond the limits of conventional sensors. Furthermore, it is envisioned to be a key enabler for cooperative automated driving. Vehicular ad-hoc networks (VANETs) provide this kind of connectivity using dedicated short range communication such as 802.11p [1] or its European counterpart ETSI ITS-G5 [2].

Multi-hop network protocols can further increase the communication range beyond one direct wireless link, e.g. around obstacles or buildings. However, discovery and maintenance of suitable forwarding paths remain a challenging task due to the dynamic nature of VANETs with high relative speeds and constantly changing topologies. While conventional ad hoc routing approaches based on proactive path maintenance or reactive (on-demand) end-to-end path discovery struggle to provide good connectivity with reasonable overhead, *geographic* routing protocols seem to be a promising candidate for multi-hop communication in VANETs [3] and are also adopted for standardization in Europe [4].

Geographic routing protocols rely on the nodes' capability to determine their own location since it is used for addressing and forwarding decisions. However, this is not a major concern in the context of driver assistance and automated driving since positioning systems such as GPS or GLONASS are already widely deployed in vehicles, e.g. for navigation or fleet tracking. Based on position information, routing decisions are made locally with each individual *hop* while progressing towards the destination. Therefore, information exchange about the network topology can be limited to the local scope significantly reducing the protocol overhead. Furthermore, it enables almost instant adaption to changes in the topology, even while a message is on its way. Geographic routing protocols can be roughly divided into *sender-based* and *receiver-based* approaches based on the strategy for next hop selection [5].

In sender-based approaches forwarding is controlled by the transmitting node. A next hop is generally selected based on status information exchanged via periodic beacons. This ensures low end-to-end delay as long as each node can process the packet instantly. However, using a single candidate as next hop makes related protocols susceptible to transmission errors caused by unreliable wireless links and leads to decreased reliability and lower packet delivery ratios.

Receiver-based (or opportunistic) approaches on the other hand shift the forwarding decision to the receiving nodes using broadcast transmissions on the wireless medium. All receivers apply a distributed function to determine the next node to rebroadcast the packet. Individual timers for each candidate are used to coordinate the channel access. If the timer expires, the packet is sent again. However, if another transmission of the same packet is overheard while waiting, the timer is canceled and the packet is discarded. Using all available forwarders increases reliability since progress can be made as long as a packet is received by at least one candidate. However, waiting times with each hop accumulate over the entire path and can lead to a substantial end-to-end delay.

To address the aforementioned problems, we proposed *Low-Delay Forwarding with Multiple Candidates* (LDMC) [6]. It combines the low latency performance of sender-based selection with the increased reliability offered by opportunistic protocols. In this paper we extend our previous work with the following contributions:

- Direct neighbors are ranked using multi-criteria decision making based on the *Technique for Order Preference by Similarity to Ideal Solution* (TOPSIS) [7] to balance different optimization goals, e.g. maximizing the distance gain per hop while maintaining high reliability.
- Neighborhood information of potential next hop candidates is considered to improve routing performance in complex scenarios by preferring well connected nodes.
- A simplified communication model and an optimal shortest path routing algorithm for this model are introduced. They are used to investigate the limits of geographic approaches for the simulated scenarios with varying network connectivity and node distribution.

Simulation results show that LDMC achieves packet delivery ratios comparable to opportunistic protocols while further improving the delay performance especially for grid-like scenarios.

The remainder of this work is organized as follows: Section II provides a review of related work while Section III describes our approach in more detail. Section IV introduces the simplified communication model and optimal routing algorithm, followed by simulation and performance evaluation in Section V. Finally, a summary of the results and an outlook on future work are given in Section VI.

II. RELATED WORK

A. Geographic Routing

Most sender-based geographic routing protocols are variations of *Greedy Perimeter Stateless Routing* (GPSR) [8] where each forwarder tries to maximize the distance covered by selecting the node that is closest to the destination as a next hop. Futhermore, it is one of the few examples providing a fall-back strategy for local maxima (dead ends). The basic approach without the fall-back strategy is also included in European standardization [4]. Naumov et al. [9] demonstrated improved reliability compared to pure distance optimization by considering speed and heading of neighbors to predict when they go out of range. Furthermore, vehicles close to intersections have been identified to play a crucial role in forwarding packets since they usually have more options for the next hop. GPCR [10], GpsrJ+ [11] and GROOV [12] apply heuristics to detect junctions in order to prefer nodes close to it. However, even though better selection strategies can improve performance for specific scenarios, relying on a single forwarder has a higher risk of transmission or node failures causing packet loss.

To overcome this dependency, opportunistic routing leveraging multiple forwarders was introduced. ExOR [13] and SOAR [14] are protocols specifically designed for Wireless Mesh Networks (WMNs). Both use a list of relay candidates compiled by the sender and attached to each transmitted packet. In addition, SOAR only selects nodes close to the direct path to the destination to avoid duplicate transmissions on diverging paths. However, the ranking metrics used in both protocols require knowledge of all inter-node loss rates which is suitable for relatively static WMNs but not for highly dynamic VANETs. *Contention-Based Forwarding* (CBF) [15], [4] and BLR [16] have shown that the combination of opportunistic principles and geographic routing can improve reliability in vehicular scenarios significantly. However, additional waiting times for the contending forwarders increases end-to-end delay. Intersections have received increased attention for receiver-based protocols as well. *TOpology-assist Geo-Opportunistic Routing* (TO-GO) [17] limits the candidate set to nodes close to a junction instead of maximizing distance progress. In TO-GO, 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.

B. Multi-Criteria Decision Making

Multi-Criteria Decision Making (MCDM) investigates strategies to structure and solve decision problems based on a number of different and potentially conflicting criteria. Starting in the 1960s [18], there has been significant progress in the field with a multitude of approaches. Among them, *Technique for Order Preference by Similarity to Ideal Solution* (TOPSIS) [7] ranks alternatives based on their distance to the ideal and negative ideal solution for a given data set.

MCDM has been applied to many different problems from diverse research areas including routing in wireless networks. Magaia et al. [19] use a combination of delay requirements and the expected transmission count to improve the end-to-end delay in Wireless Multimedia Sensor Networks. Moreover, Suh et al. [20] apply a TOPSIS approach to Wireless Sensor Networks taking the potential of distance, residual energy and queue length of a candidate into account. MAODV [21] - an extension of the well known Ad hoc On-Demand Distance Vector (AODV) routing - uses MCDM to combine up to 8 different cross-layer criteria to improve the stability of managed links. Finally, Johnson and Silas [22] designed a service discovery protocol for vehicular networks based on position information, load balancing, energy efficiency and other selected Quality-of-Service (QoS) parameters. Their simulations show that it can reduce the discovery time while providing high success rates.

III. LOW-DELAY FORWARDING WITH MULTIPLE CANDIDATES

A. Motivation

The goal of our LDMC approach is to provide reliable multi-hop routing of unicast messages with low end-to-end delay. Opportunistic protocols already provide very good reliability. However, distributed coordination of the forwarders is generally realized through timer-based contention where each node applies a delay before the packet is retransmitted. The function to calculate the individual delay has to balance two opposing goals: a) short waiting times to reduce the end-to-end delay and b) sufficient timely separation among candidates to avoid collisions on the wireless medium. Selecting a short interval is beneficial if the network density and therefore the number of contending nodes is low since overall delay is reduced. However, applying the same setup to a dense scenario will lead to many collisions due to similar waiting times for multiple contenders.

In addition, the end-to-end delay performance of approaches where the individual waiting time is based on relative positions or distances, e.g. geographical progress towards the destination [15], [16] or distance from a target node [17], highly depends on the distribution of the nodes. Equation 1 shows the delay function of the CBF algorithm specified in [4] as an example:

$$t_{CBF} = \begin{cases} t_{max} + \frac{t_{min} - t_{max}}{d_{max}} \cdot p, & \text{if } p \leq d_{max} \\ t_{min}, & \text{if } p > d_{max} \end{cases} \quad (1)$$

where the times t_{min}, t_{max} and the distance d_{max} are configuration parameters and p is the distance progress towards the destination compared to the previous node. Here, an uneven distribution of nodes leads to a long unused period without contention until finally the first candidate tries to retransmit. In a worst case scenario, only nodes close to the current sender can be reached directly. Thus, up to t_{max} waiting time will be applied without any contention before that. Assuming the default values specified in [4] this can lead to up to 100 ms per hop which is not acceptable for applications with stringent delay requirements. To avoid the aforementioned issues, LDMC uses the transmitter of a packet to indirectly coordinate the contention among receivers.

B. Protocol Design

1) Assumptions: similar to other geographic routing protocols, the current position of the destination has to be known by the source before sending a packet. This can either be achieved through an additional *Location Service* [4] or with information contained in already received packets. However, the specific implementation is out of the scope of this paper. Therefore, we assume the destination position to be known a priori with all algorithms in our evaluation. Furthermore, basic information about neighbors in direct communication range is exchanged via periodic network layer beacons containing a station identifier, the current position and the number of direct neighbors.

2) Algorithm: In each forwarding step, the current node n specifies an ordered list of forwarders $F = \{f_0, \ldots, f_i\}$ where each f_k is the station identifier of a direct neighbor of n that is closer to the destination than n. The order of the elements in F is determined using the TOPSIS approach described in section III-C. F is added to the header of the packet before it is transmitted using the broadcast primitive of the wireless medium. A configuration parameter i_{max} is used to limit the header size. If $|F| > i_{max}$, only the first i_{max} entries are added to the header. More candidates increase reliability through additional relay nodes while shorter lists reduce the overhead caused by additional fields in the packet headers.

Upon reception of a packet, each node checks if it is the destination. If so, the payload is provided to the higher layers. If not, the receiver takes part in the contention for rebroadcasting if its local identifier is part of the forwarder list contained in the header. Decentralized coordination of rebroadcasting attempts is achieved with a timer-based approach where the waiting time t_{wait} is based on the position p_c of the receiver in the list (starting with 0 for the first entry):

$$t_{wait} = p_c \cdot t_f \quad (2)$$

t_f specifies the time difference between two consecutive list entries. It is a configuration parameter that should be large enough to sufficiently separate channel access attempts over time to avoid packet loss due to collisions. Similar to other opportunistic approaches, a node cancels its timer and drops the packet if it overhears another node forwarding the same packet during its waiting time.

3) Extension: Reliability of LDMC can be improved - especially for forwarder lists with only few entries - by allowing receiving nodes not in the list to still participate in the forwarding process. This can compensate for outdated status information and will also include candidates that the transmitting node n was not yet aware of. Since there is no list index to determine the waiting time, they apply the basic CBF procedure instead. However, this should only be the case if all preferred entries in the list failed to forward the packet. Thus, the CBF period should start after the waiting duration implied by the length of the forwarder list:

$$t_{wait,CBF} = |F| \cdot t_f + t_{CBF} \quad (3)$$

where $|F|$ is the size of the forwarder list and t_{CBF} is the CBF timeout duration calculated with Equation 1.

C. Ranking Candidates with TOPSIS

The ranking of the nodes for the forwarder list plays a crucial role for the performance of our LDMC approach: The more suitable the selection of the first list entries, the smaller the end-to-end delay.

1) Criteria: Most geographic routing protocols aim to maximize the distance covered in each step and thus minimize the number of hops. The reason for that is threefold: a) each additional transmission takes time and thus increases the delay, b) it also occupies the shared medium and thus requires additional resources, and c) it increases the potential for packet loss since wireless links are unreliable. This metric is usually defined in terms of *distance progress* $p(n, c)$ from the previous node n to the current node c:

$$p(n, c) = dist(n, d) - dist(c, d) \quad (4)$$

where d is the destination and $dist(x, y)$ is the distance between x and y.

However, received signal strength and thus reliability decrease with distance. It can be more beneficial to tolerate additional hops with more reliable links instead of trying to reach a node that is barely in range. Instead of a ranking based on position, neighbors with recent status updates could be preferred over those with older entries instead. The selection of suitable candidates depends on up-to-date information [23] and recent contact increases the chance of still being in range.

Furthermore, even though our previous version of LDMC showed promising results [6], it struggled in grid-like scenarios since it did not prefer crucial relay points at intersections. Thus, we propose to additionally use the number of direct neighbors as a metric to prefer well connected nodes - probably at an intersection or open space - over candidates with less connectivity.

In summary, candidates are ranked by three different and potentially opposing criteria:

- D: distance progress towards the destination
- A: age of the status information (time since the last update)
- N: number of direct neighbors

2) Ranking: We selected TOPSIS to rank the forwarding candidates. It has several beneficial properties in this context. Criteria can have inhomogeneous dimensions and units since normalization is applied in the process. Furthermore, ranking is based on relative comparison of the alternatives in the current set of options. Thus, absolute parameter values required to be suitable for all scenarios can be avoided, e.g. t_{max} and d_{max} from CBF (see Eq. 1).

The procedure for ranking all candidates is as follows:

1) From all available neighbors, select only those that are closer to the destination than the current node. This step is required to avoid routing loops and to ensure that the process converges towards the destination. Result is the list of candidates $F = f_1, ..., f_k$ with k elements.
2) Create the $k \times l$ decision matrix M with elements x_{ij} denoting the rating value of candidate f_i for the criterion C_j. Since we have three criteria: $l = 3, j = 1, 2, 3$.
3) Normalize the decision matrix M by applying Eq. 5 to each element:

$$x'_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{k} x_{ij}^2}} \tag{5}$$

4) Create the weighted normalized decision matrix by multiplying each value x'_{ij} with the weight w_j for the specific criterion:

$$x''_{ij} = w_j x'_{ij} \quad \text{with } i = 1, ..., k; j = 1, ..., l \tag{6}$$

5) Determine the ideal solution S^* and the negative ideal solution S'. S^* consists of elements s_j^* where each element represents the best value among all candidates for criterion C_j. S' accordingly consists of elements s'_j with the worst values for each C_j.
6) Calculate the distance of each candidate from S^* and S'. In this case, we apply the Euclidean distance:

$$D_i^* = \sqrt{\sum_{j=1}^{l} (s_j^* - x''_{ij})^2} \tag{7}$$

$$D'_i = \sqrt{\sum_{j=1}^{l} (s'_j - x''_{ij})^2} \tag{8}$$

7) Calculate the relative closeness C_i^* to the best and worst solution using Eq. 9. Values close to 0 indicate that the candidate is similar to the worst solution, whereas a value close to 1 indicates that the candidate is similar to the ideal solution:

$$C_i^* = \frac{D'_i}{D_i^* + D'_i} \tag{9}$$

8) Sort all candidates according to C_i^* in descending order. The candidate most similar to the ideal solution S^* will be the first entry.

IV. OPTIMAL ROUTING WITH A SIMPLIFIED COMMUNICATION MODEL

Routing a packet from source to destination can fail for a number of reasons. Transmission errors and collisions on the wireless link lead to immediate packet loss. Selecting unsuitable forwarders can unnecessarily increase the number of hops and therefore the error probability. And in some cases there is simply no suitable path available: the network is partitioned. In addition, with geographic approaches there is the chance that all paths end in a local optimum where no nodes closer to the destination are available. For the latter case, GPSR [8] provides the so-called *Perimeter Mode* to route a packet around such an optimum. However, it is not part of the *Greedy Forwarding* standardized in [4].

Most of these issues directly depend on the specific scenario: node distribution, node density and obstacles for the radio propagation that heavily influence connectivity. Therefore, characterizing a scenario with respect to its best case potential can provide better insight on achievable performance. The described model and routing algorithm are intended for comparison and thus complementary tools to the more detailed simulation provided in Section V.

A. Communication Model

Wireless communication in network research is usually modeled with stochastic processes describing channel behavior, reception probability etc. based on environmental factors. However, in order to find optimal short paths a deterministic communication model is needed. It describes under which conditions two nodes can successfully communicate with each other using a direct link.

In our model we extend the well known *Unit Disk Graph* [24] with support for obstacles blocking the communication between two peers. Nodes are connected if:

1) They are within a predefined transmission range r_{tx} and
2) No obstacle boundary intersects with the straight line connecting both nodes, i.e. they are within line-of-sight.

If both conditions are true, perfect connectivity without packet loss and collisions is assumed. In any other case, no communication is possible at all.

B. Shortest Path Optimal Routing

Assuming global knowledge within the simulation environment, a shortest path with respect to the number of hops can be found with the following algorithm:

```
**Require:** source $s$, destination $d$, set of all nodes $N$,
Initialize connectivity tree $T$ with root $s$
$C = N \setminus \{s\}$, $L_{in} = \{s\}$, $L_{out} = \emptyset$
**while** $C \neq \emptyset$ **and** $L_{in} \neq \emptyset$ **do**
    **for all** $c \in C$ **do**
        **for all** $l \in L_{in}$ **do**
            **if** $connected(c, l)$ **then**
                $C = C \setminus \{c\}$
                $L_{out} = L_{out} \cup \{c\}$
                Add $c$ as child of $l$ in $T$
```

```
                if $c = d$ then
                    return Path from $s$ to $c$ in $T$
                end if
            end if
        end for
    end for
    $L_{in} = L_{out}$, $L_{out} = \emptyset$
end while
return No path
```

The described strategy will utilize all remaining nodes in each step along the path and is therefore called *select all*. However, most geographic routing protocols only consider candidates closer to the destination as potential forwarders. Hence, we define a second strategy *select closer* following this approach. It limits the paths found by the optimal router to those discovered by protocols requiring constant progress towards the destination. The difference between both strategies indicates how much improvement could be expected from additional mechanisms specifically dealing with local routing optima.

V. 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] as well as the optimal routing from the previous section. Line forwarding capabilities are investigated with a Freeway scenario in Section V-B whereas a Manhattan Grid with buildings is used to provide more challenging tasks in Section V-C.

A. Simulation Environment and Parameters

The simulation environment consists of the network simulator ns-3 [25], the traffic simulator SUMO [26] and the ETSI ITS protocol stack implemented by the ezCar2X framework [27], [28]. Multiple simulations of the same parameter set with different random seeds were run using [29]. LDMC was also implemented within the ezCar2X framework reusing most headers and data structures from the ETSI ITS GeoNetworking standard [4]. The only deviations are: a) the inclusion of the current number of direct neighbors in beacons and b) adding the forwarder list to the basic header for each packet transmission.

The main simulation models and parameters are summarized in Table I, including stochastic channel models with fading. We selected four different weight combinations $W = \{w_D, w_A, w_N\}$: W_D, W_A, W_P using only one criterion and W_{comb} using an equal combination of all three. However, future work has to investigate the optimal selection of the different criteria weights in more depth.

One additional aspect is worth noting: Nodes are removed from the neighbor table if no beacon was received from them for the specified *Neighbor Timeout*. In contrast to the default location table lifetime of 20 s in [4] we select a shorter time of 3 s to accommodate for fast changing environments. Missing more than two beacons in a row suggests an unavailable link. However, all simulations were also repeated with a 20 s timeout leading to a severe degradation of achievable performance across all parameter sets. The only exception was CBF which does not rely on neighbor information provided via beacons for routing and therefore showed no significant impact.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Standard	802.11p
Tx Power, Tx Rate	15 dBm, 6 Mbps
Propagation Model (Freeway)	Nakagami [30]
Propagation Model (Grid)	Chen et al. [31] with [32]
Packet Size, Packet Interval	300 Bytes, 0.1 s
Beacon Interval	1.0 s . . . 1.25 s
Neighbor Timeout	3 s
i_{max}, t_f	10, 1 ms
W_D	$\{1, 0, 0\}$
W_A	$\{0, 1, 0\}$
W_N	$\{0, 0, 1\}$
W_{comb}	$\{\frac{1}{3}, \frac{1}{3}, \frac{1}{3}\}$
Simulation Runs	32
Duration per Run	1000 s

B. Freeway Scenario

The *Freeway* scenario consists of a 4 km highway with 3 lanes in each direction. Vehicles drive on all lanes with randomized departure times and speeds varying between 80 and 130 km/h. Once stabilized, there are on average 270 vehicles active in the simulation. Network connectivity has been varied with different equipment rates r_{eq} ranging from 10% to 100%. For each transmitted packet a random $(source, destination)$ pair is chosen among all currently active nodes. However, nodes close to both ends of the highway were excluded to avoid edge effects.

Applying the optimal approach presented in Section IV, both selection strategies show identical results. This is expected since there are no local optima in a straight line forwarding scenario. As shown in Fig. 1, a higher communication range is required with lower penetration rates to provide sufficient connectivity. However, even with only 20% of the vehicles equipped, perfect packet delivery ratio can be achieved with 600 m communication range or more. With less range or fewer nodes the packet delivery ratio drops significantly indicating a partitioned network.

For the LDMC performance, we first investigate the different alternatives for the criteria weights. Fig. 2 shows the achieved delivery ratio under selected delay constraints. While selection based on the age of the neighbor status performs best among the single criteria for the dense scenario, ranking according to distance is a better choice with lower penetration rates. Nevertheless, the combination of all criteria using W_{comb} provides better results than the individual metrics balancing distance gain per hop against information freshness. Approximately 69% of the packets are delivered within 10 ms and more than 90% in less than 100 ms.

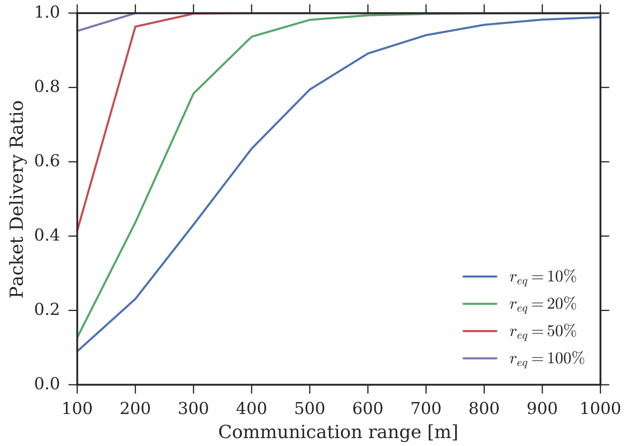

Fig. 1. Freeway Scenario: Packet delivery ratio for the simplified communication model with optimal shortest path routing, only the *select all* strategy is shown.

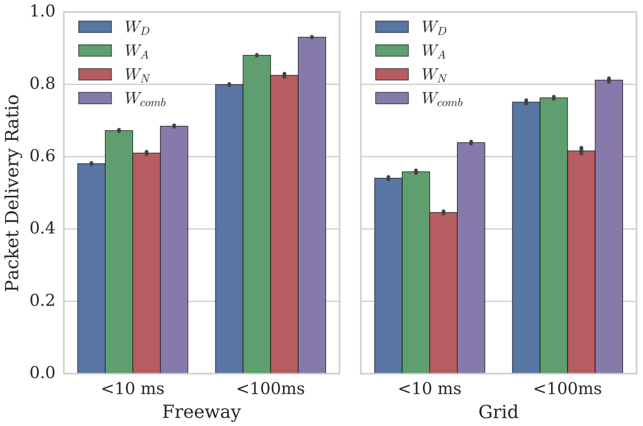

Fig. 2. Comparison of packet delivery ratios for different weight combinations and delay constraints in the Freeway ($r_{eq} = 1.0$) and Grid ($r_{dep} = 2.0\ \frac{veh}{s}$) scenario. The CBF extension for LDMC is not used.

Comparing LDMC with existing algorithms like Greedy and CBF highlights the advantages of our approach for delay-sensitive applications. As shown in Fig. 3 both standardized algorithms deliver roughly 30% of the packets within 50 ms while LDMC already exceeds 90%. Without any timing constraints, the inherent reliability of CBF shows its advantage performing slightly better than our approach. However, end-to-end delays of more than 400 ms may not be acceptable for some applications. Still, CBF and LDMC are capable of getting close to perfect connectivity as indicated by the optimal router. Adding the CBF extension to LDMC improves performance slightly in the unrestricted case but at the price of increased channel usage as explained in Section V-D.

C. Manhattan Grid Scenario

The *Manhattan Grid* scenario consists of 4×4 blocks each of size 360 m × 100 m surrounded by single lane roads connected with uncontrolled intersections. Buildings are placed between roads with their walls 15 m away from the road center. Vehicles take random trips with a target speed of 50 km/h. In contrast to the Freeway scenario network density is controlled via the departure rate $r_{dep} = \{1...2\}$ vehicles per second. With $r_{dep} = 1$, traffic flows freely. However, with $r_{dep} = 2$, vehicles start to queue at intersections and therefore remain longer in places with good connectivity. Similar to the freeway scenario, a random $(source, destination)$ pair is chosen for each packet.

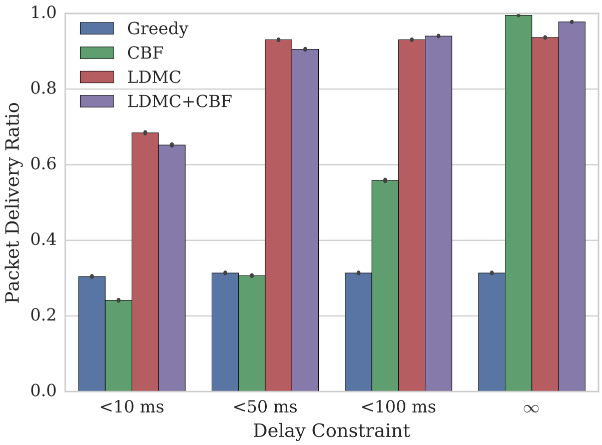

Fig. 3. Freeway Scenario: Packet delivery ratio for different delay requirements comparing LDMC and LDMC+CBF using W_{comb} with existing algorithms ($r_{eq} = 1.0$).

Fig. 4 shows the packet delivery ratio for the optimal router with various vehicle departure rates and both selection strategies. The results show that for all chosen parameters the packet delivery ratio reaches a saturation point at about 400 m of communication range. Increasing the range further has little effect on the connectivity. In contrast to the Freeway scenario, the *select closer* strategy performs noticeably worse than the *select all* approach. The gap between strategies is most prominent for the setup with the lowest node density. However, even with more vehicles in the scenario, conventional approaches relying on progress towards the destination with each step can at best reach a packet delivery ratio of 94% for $r_{dep} = 2$ and 92% for $r_{dep} = 1.7$ vehicles per second. Another observation worth mentioning is that even the *select all* strategy with unlimited communication range fails to reach perfect packet delivery if the node density is too low. This behavior is caused by the lack of suitable forwarding nodes at intersections making it impossible to route a packet *around the corner*.

The analysis of different weight combinations leads to results similar to those of the Freeway scenario with one exception: the significantly decreased delivery ratio if only the number of neighbors is considered. This criterion was chosen to select nodes close to intersections which - if applied alone - it does too well. Packets regularly get *stuck* in the region around an intersection since there are multiple nodes with good connectivity in close range. Once there, other nodes nearby are preferred as the next hop and thus provide little progress. It also explains why the effect is less prominent with lower vehicle densities. Nonetheless, the need to balance the selec-

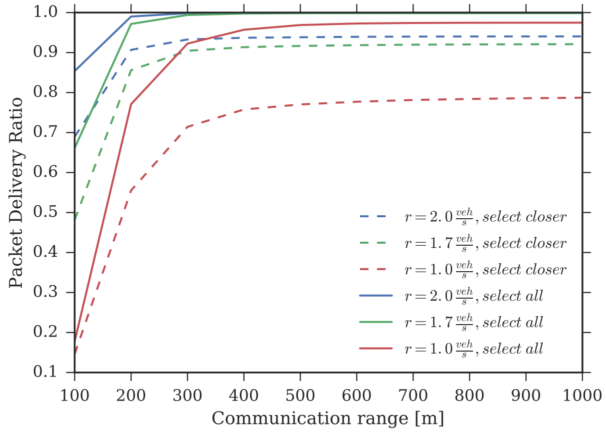

Fig. 4. Manhattan Grid Scenario: Packet delivery ratio for the simplified communication model with optimal shortest path routing for both selection strategies.

tion of well connected nodes with other optimization goals like sufficient distance progress is obvious and its benefits are shown with the combined weight W_{comb} outperforming all other options.

Fig. 5 shows LDMC with and without CBF extension in comparison to Greedy forwarding and CBF. Similar to the Freeway scenario, both standardized algorithms show poor performance if delay constraints of 100 ms or less are considered. Greedy reaching its maximum of 29% delivery ratio already after few milliseconds even surpasses CBF in the low latency segment, while CBF again demonstrates high reliability without any delay constraints. LDMC is capable of delivering 80% of the packets within 50 ms but falls short of reaching more destinations afterwards. Adding the CBF extension to LDMC improves long term reliability by more than 10% bringing it close to CBF. Furthermore, both protocols achieve packet delivery ratios close to the optimal router using the *select closer* strategy for all traffic densities. The worst case difference between the optimal router and LDMC of around 7% was found in the scenario with $r_{dep} = 1$.

In summary, our proposed LDMC scheme shows substantial improvement for end-to-end delay constraints below 100 ms while CBF appears to be slightly more reliable if latency is no concern. Furthermore, LDMC is more predictable in terms of delay distribution delivering almost all packets within 50 ms and thus allowing for shorter timeout values on higher layers. Since both protocols share a lot of similarities, they can easily be combined. Based on the requirements of the application, the network layer can apply our LDMC scheme for packets with strict latency requirements while forwarding less demanding requests using an empty forwarder list and thus falling back to standard CBF.

D. Overhead

Efficient utilization of available channel resources is another important requirement for routing protocols in VANETs. All compared approaches share the same packet structure and

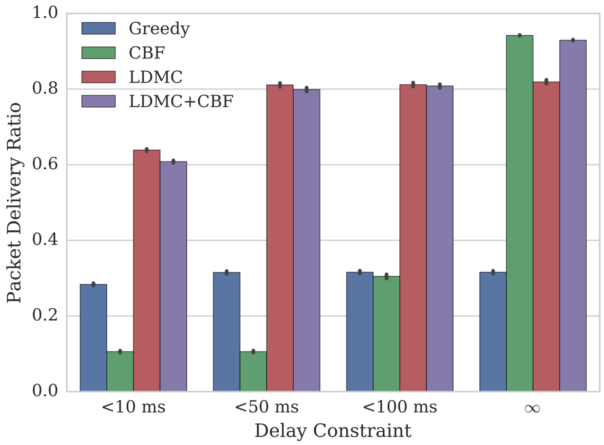

Fig. 5. Manhattan Grid Scenario: Packet delivery ratio for different delay requirements comparing LDMC and LDMC+CBF using W_{comb} with existing algorithms ($r_{dep} = 2.0\ \frac{veh}{s}$).

TABLE II
AVERAGE TIMES FORWARDED

	Greedy	**CBF**	**LDMC**	**LDMC+CBF**
Freeway	1.156	16.488	4.927	10.700
Grid	4.875	28.860	6.787	20.241

TABLE III
CHANNEL BUSY RATIO [%]

	Greedy	**CBF**	**LDMC**	**LDMC+CBF**
Freeway	2.222	3.759	2.435	3.523
Grid	4.755	5.252	2.717	4.759

beacon frequency. The main source for differences is therefore the number of times a packet is actually transmitted while forwarding. Furthermore, LDMC may add up to 60 Bytes (10 entries) to the packet header for the forwarder list. In all simulations we measured the channel busy ratio (CBR) at several locations. We only discuss the results of the probes in center of the most dense scenarios here. However, the observed trends are consistent across all measurements.

Table II shows the average number of times a packet was handed from the network to the access layer while forwarding (including attempts that could not be delivered) while Table III summarizes the measured CBR considering all transmitted packets including beacons. The surprisingly large values for the Greedy approach in the Grid scenario can be explained by the broadcast fallback specified in [4] if no suitable neighbors are found. This can lead to a sudden *broadcast storm* if sufficient neighbors are available but none of them is closer to the destination.

Overall LDMC demonstrates to be very efficient in both categories, reducing the number of forwarding attempts and thus channel usage compared to CBF while maintaining high reliability. However, even though adding the CBF extension can improve reliability further it leads to a severe increase in resource consumption - especially in the grid scenario.

VI. CONCLUSION

In this paper we proposed LDMC, a geographic routing protocol for vehicular applications with strict latency requirements. Multi-criteria decision making is applied to rank neighbors according to their position, time since the last update and number of connections. Our simulations show that the priority-based coordination of the candidates significantly decreases end-to-end delay while maintaining good reliability. In the selected grid scenario, LDMC delivered up to 80% of the packets within 100 ms while Greedy and CBF achieved only 30% in the same time frame. In addition, comparison with an optimal routing algorithm revealed limits for approaches relying on distance progress in more complex scenarios.

As a next step we plan to investigate the optimization potential with respect to different protocol parameters, e.g. the weights for the individual ranking criteria, the maximum number of candidates and the time delay between list entries. With the large performance differences among the chosen scenarios, we furthermore intend to deploy LDMC and other protocols in a more realistic environment like [33]. Finally, the performance impact of additional traffic on the wireless channel has to be evaluated as well.

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