DAZL: Density-Aware Zone-based Packet Forwarding in Vehicular Networks

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***Abstract*—Multi-hop message forwarding based on geographic coordinates is a fundamental building block for vehicular communication. However, the unstable links and wide range of node densities make it challenging to design an algorithm suitable for vehicular use. We introduce DAZL, a new forwarding protocol that combines three concepts in a novel way. First, multiple nodes cooperate in packet forwarding. Compared with traditional single relay schemes, this provides robustness against changes in topology and packet delivery rates. Second, network-layer slotting is used to control duplication and contention in high density scenarios. Third, a distributed prioritization algorithm is used to opportunistically maximize hop length. Through both experiments and simulations, we show that DAZL provides improvements of up to 60% in throughput over single relay forwarding, while ensuring low latency and replication.**

I. Introduction

Vehicular Ad-Hoc Networks (VANETs) aim to improve land transportation by enabling novel applications in areas ranging from safety to traffic efficiency and infotainment. Many of these applications, such as internet access, sensor data gathering and cooperative car routing, require multi-hop communication for increased coverage [1]. While cellular is sometimes an option, vehicular networks provide advantages in terms of latency, bandwidth and cost, making efficient multi-hop communication an important problem.

Multi-hop packet forwarding in VANETs is challenging for two reasons. First, as a result of the vehicles' mobility, the rich scattering environment, and obstructions created by obstacles, link quality is highly variable [2]. This leads to very dynamic packet delivery rates and a large gray-zone of partial connectivity [3]. Second, node densities vary greatly, both in space and time, which calls for an adaptable protocol. When vehicles are sparse, forwarding must be aggressive to prevent packet loss. In contrast, in a traffic jam, forwarding must be conservative to avoid congestion collapse.

Previous work in VANET routing has focused on a single relay paradigm where, at each hop, a single neighbor is chosen to forward the packet. This approach is susceptible to the gray-zone phenomenon found in VANETs because it relies on the quality of a single link. Some protocols (e.g. [4], [5]) further aggravate this problem by choosing the longest possible hop, which, being at the edge of the radio range, tends to be the most unstable. Based on this observation, we present a new packet forwarding algorithm named DAZL (read dazzle) for Density-Aware Zone-based Limited forwarding. The algorithm combines three key ideas in a novel way.

First, the presence of multiple vehicles within communication range can help address the link instability issue, because channels to different vehicles experience different fading conditions. To exploit this, DAZL nodes do not forward packets to a specific neighbor, but instead to a geographic region, or zone, and any vehicle in that zone can forward the packet. Since the next-hop is not selected a priori by the sender, the forwarding operation can opportunistically use the best available channel. We will refer to this as "vehicle diversity". Second, through the use of a distributed prioritization algorithm, this approach can *opportunistically* give preference to forwarders closer to the destination, if they are available, thus reducing the number of hops. Finally, to deal with highly variable vehicle densities, we make DAZL density-aware. Specifically, in high density scenarios, we reduce the fraction of vehicles that attempt to forward a packet, thus minimizing contention in the network.

DAZL combines the general ideas of diversity and opportunistic transmission, which have been used successfully in infrastructure and mesh networks, and applies them to the VANET context. Previous opportunistic protocols have relied on topology information [6], [7] and shared channels [8] for coordination, both of which are not available in VANETs. DAZL's key contribution is therefore a novel distributed and implicit relay coordination algorithm that allows potential relays to cooperate while reducing replication and interference.

The remainder of the paper is organized as follows. Section II describes the challenges in VANET forwarding. Section III presents our approach and Section IV the other benchmarked protocols. Sections V and VI present our experimental and simulation evaluations, respectively. Section VII discusses related work and Section VIII concludes the paper.

II. Challenges

A. Link instability

Traditional routing schemes build on the premise that nodes have a fixed or slowly changing set of neighbors and that neighbors are well connected to each other. However, measurements have shown that these assumptions do not hold for VANETs, where topology changes quickly and links are

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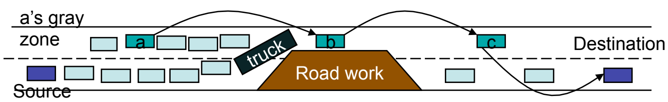


Fig. 1: Existing proposals suffer with link instability and variable node densities.

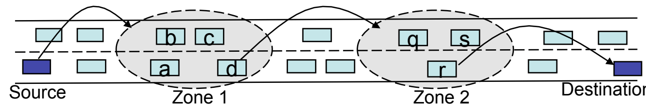


Fig. 2: The proposed zone-based forwarding scheme.

often poor. The reasons for this instability stem from the combination of a rich scattering domain and high mobility. Depending on location, roads can be lined with trees, buildings and mounds that scatter the signal and create multipath effects that change quickly with even small movements, resulting in large fluctuations in link quality. Node movement also leads to changes in shadowing conditions. For example, when a vehicle turns the corner of a building, its signal is immediately attenuated [2]. Moreover, even when nodes are stationary, changes in line of sight conditions can affect communication. For example, in Figure 1, a tall truck is about to come in between nodes a and b, blocking their line of sight.

Traditionally, the path between source and destination is defined as a sequence of specific nodes. In the example in Figure 1, cars making up the path are shown in green. Path selection strategies vary. In periodic routing schemes, routes are precomputed and next hops stored in a routing table. In source based routing, e.g. [9], the path is selected by the source, and stored in the packet header. These strategies are problematic because routes quickly became obsolete in the dynamic VANET environment. With geographic routing, e.g. [10], the next-hop is selected by the previous node based on its neighbors' and the destination's coordinates. This on the fly relay selection makes geographic forwarding more adaptive, and a popular choice for vehicular protocols.

Recently, Bai et al [3] observed that, unlike other environments, vehicular does not have a large transmission range within which reception is (near) perfect. Instead, most of the radio range is a gray-zone with intermediate packet delivery rates. In other words, there are very few good links in VANETs, and the ones that are, tend to be short and thus unattractive for forwarding. Because of this, relying on a single next-hop node to forward a packet like existing protocols do is dangerous. We propose to address this problem by leveraging "vehicle diversity": allowing multiple vehicles, subject to different fading condition, to cooperate in forwarding packets. We further detail vehicle diversity in Sections III-A and III-B.

B. Hop length tradeoff

The link instability encountered in vehicular networks makes the selection of a good next hop difficult. Geographic routing is a good option since the choice is made as late as possible. Note, however, that any protocol faces a fundamental tradeoff. Picking a nearby node results, on average, in a higher packet delivery rate, but it will require more hops to reach the destination. Picking a more distant node reduces the number of hops, but lower channel quality will result in increased losses, and thus more retransmissions. It may also increase interference losses, e.g. as a result of hidden terminals. Because of this, managing this tradeoff to optimize throughput is difficult.

We propose to address this problem by prioritizing vehicles. In our solution, nodes closer to the destination are given priority, but nodes closer to the sender step in when no such long-range nodes are available. This maximizes hop length without compromising reliability. Section III-D provides more details.

C. Variable node densities

Traffic density varies greatly in space and time. Bai et al [11] reported inter-vehicle spacings for a Toronto freeway ranging from 6 to 500 meters, depending on the hour of the day. Different densities can even be found simultaneously on the same road, e.g. due to road work—Figure 1.

Low density scenarios are susceptible to network partitioning, which is usually addressed through store and carry procedures. High densities create another class of problems. For example, the more vehicles there are, the more messages are likely to be sent, increasing congestion. This will create interference losses that will further compound the previously mentioned link instability issue, and it can even lead to collapse if the high load cannot be handled by the 802.11p backoff mechanism. Network-layer protocols have to adapt and control the burden placed on the MAC layer.

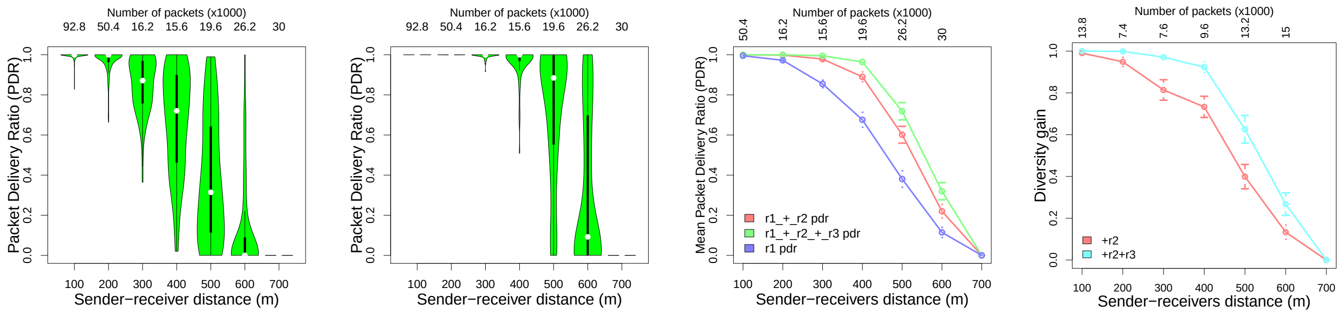
Some proposals (e.g. [4], [12]) have actively tried to guide packets towards dense regions in an attempt to increase reliability; while this may be effective in low density scenarios, it is problematic when node densities are high. We tackle this issue by limiting the number of potential forwarders and spreading them in time, as explained in Section III-C.

III. PROTOCOL DESIGN

A. Vehicle Diversity

In traditional forwarding algorithms, packets are forwarded to a specific next-hop node, which is problematic in VANETs: since links have large gray zones, very few links (other than very short ones) are stable. To counter this, DAZL uses zone-based forwarding, a new paradigm in which packets are forwarded not to a specific node but to a geographic zone located between the previous hop and the destination—Figure 2. Any car in the zone can then forward the packet. Due to their physical separation, nodes will experience different fading, line of sight and interference conditions, so having multiple potential forwarders decreases the likelihood of packet loss.

In order to assess the potential gains of vehicle diversity we performed an experiment where we parked a sender vehicle and had 3 receivers drive a circuit around it, keeping close



(a) PDR of a single receiver

(b) Combined PDR of 3 receivers

(c) Mean PDR for different receiver combinations

(d) Diversity gain from adding receivers

Fig. 3: Evaluation of the benefits of using vehicle diversity to mitigate channel variability. The plots show that vehicle diversity greatly reduces the size of the gray-zone of partial connectivity found in vehicular networks.

together and exchanging positions periodically like cyclists riding in a group. The vehicles were equipped with NEC LinkBird-MXs, a platform for IEEE 802.11p-based vehicular communications [13]. One hundred 500 byte messages were sent every second at a data rate of 6 Mbps and a transmit power of 18 dBm in a 10 MHz channel centered at 5.9 GHz.

Figure 3a shows a violin plot of the Packet Delivery Rate (PDR) of the first receiver, **r1**. PDR is sampled every second and samples are grouped into 100 m sender-receiver distance bins. The violin plot combines the median and quartiles from a boxplot with a kernel density plot, allowing us to see both the distributions' shape and main parameters. A large gray-zone of partial connectivity can be observed, with intermediate PDRs between 300 and 600 m. In Figure 3b we can see what happens when we consider a packet to be delivered as long as at least one of the three receivers is able to decode it. The reduction in the gray-zone's size is clear, with partial connectivity being observed only in the 500 and 600 m distance bins.

The mean PDR for 1, 2 and 3 receivers is plotted in Figure 3c as a function of distance. Going from a single receiver **r1** to 2 receivers, **r1 + r2**, provides a 20% PDR increase. A third receiver, **r3**, adds an additional 10%.

We define diversity gain as the ratio of messages that can be recovered due to vehicle diversity divided by the number of messages lost by the reference receiver, **r1**. Figure 3d shows this gain as a function of distance. We observe that **r2** allows us to recover at least 75% of losses up to 400 m. Adding **r3** to **r1** and **r2** eliminates 95% of all losses up to the same distance.

These results show that there are significant benefits to be had by a protocol that is able to exploit vehicle diversity. Next, we discuss how such a protocol can be realized.

B. A Zone-based Forwarding Protocol

DAZL, for Density Aware Zone-based Limited forwarding, is a geographic forwarding protocol that uses zone-based forwarding to overcome the gray-zone phenomenon. In this section we present the high-level algorithm, while the following ones provide further detail on each component.

We assume that nodes know their own coordinates and are able to obtain their one-hop neighbors' coordinates from periodically broadcast beacons [14]. The destination should be location-addressable through prior knowledge or a location service [15]. The packet header stores three addresses: original source, destination, and the forwarder ("previous hop") that sent the packet. Each address includes both node identifier and geographic coordinates for the car. At each hop, each vehicle receiving the packet executes the following protocol:

1) Based on its position and the header information, check whether it is closer to the destination than the previous hop. If it is not, drop the packet.
2) Run a ranking algorithm to compare its utility as a forwarder with the utility provided by other potential forwarders in its neighborhood.
3) If the node is thought to be one of the n best potential forwarders then it is said to be in the *forwarding zone*. Otherwise, it drops the packet.
4) If the vehicle is in the zone, it waits for a period of time inversely proportional to its rank before forwarding the packet. We call this *rank-based slotting*.
5) If, while in the waiting state, the vehicle overhears another vehicle forwarding the packet, it learns that its transmission is not needed and cancels the operation.

The *implicit acknowledgment* scheme in the last step is also used by the previous hop to learn about the forwarding operation's success. Losses are detected by a timeout and handled through retransmission. If nodes do not hear each other's forwardings, replication can occur. To mitigate this issue DAZL implements a simple duplicate suppression scheme. Each node keeps a history of overheard messages and uses it to check whether incoming messages should be dropped.

As more receivers are added in high density scenarios, increased contention starts to negate the benefits of vehicle diversity. DAZL controls this tradeoff by limiting the amount of forwarders to a number n, a parameter. If we set n to say, 5, we can both ensure reliability in low density scenarios and reduce contention in high density situations.

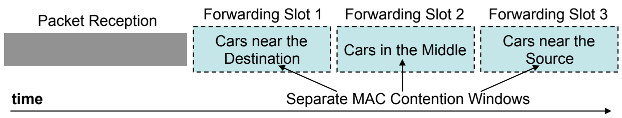


Fig. 4: Slotting spreads the potential forwarders in time according to their locations.

The distributed ranking algorithm used by DAZL allows nodes to coordinate without explicit communication, reducing overhead. The ranking also serves as a prioritization mechanism that enables us to maximize hop length. The delay introduced at the forwarding level, in addition to the limit number n of forwarders, work to reduce replication and contention in high density situations. We discuss these mechanisms in more detail below.

The forwarding protocol here described is able to forward packets along a road between source and destination coordinates (e.g. in a highway). More complex topologies can be supported by adding more detailed path information to the packet header, e.g. a sequence of roads to traverse.

C. *Forwarder coordination through slotting*

While the redundancy introduced by zone-based forwarding is inherently beneficial in sparse areas, the challenge posed by high densities must be addressed. If too many nodes inside the forwarding zone try to forward simultaneously, 802.11p's backoff mechanism may not be able to avoid high packet collision rates. Moreover, having too many forwarders may increase duplicates, adding unwanted load on the network.

The 802.11p MAC Distributed Coordination Function (DCF) already implements some basic coordination for us. In DCF, nodes that detect a busy channel execute a backoff procedure in which each node randomly chooses a slot from a contention window with (typically) 16 slots and awaits its turn. If the channel is now found to be free, the packet is sent. Otherwise, the procedure is repeated. While this is sufficient to avoid collisions between a modest number of nodes, it is not sufficient in dense scenarios. Moreover, MAC-layer slots are so short that they do not allow enough time for nodes that are waiting to forward to overhear other forwarders' transmissions and cancel theirs. Finally, they do not provide prioritization.

Our solution is to introduce an additional level of slotting at the network layer. DAZL divides the time after a packet reception into a number of forwarding slots—Figure 4. Potential forwarders distribute themselves over the slots without explicit coordination. The duration of each slot is an important parameter. If the slots are too long, latency will suffer. If they are too short, nodes in different forwarding slots may still contend at the MAC level if their contention windows overlap. Ideally, slots should be just slightly longer than the average MAC layer contention window so that nodes in different slots do not compete but also do not wait around needlessly.

D. *Forwarder prioritization through ranking*

Long distance hops are desirable because they mean fewer hops to reach the destination, and consequently, lower latency, traffic load, and interference. Therefore, we want to prioritize the nodes closest to the destination. However, when these nodes do not receive the packet, we want nodes further away to step in and ensure reliability, effectively addressing the hop length tradeoff pointed out in Section II.

DAZL achieves prioritization through a smart assignment of nodes to forwarding slots: nodes close to the destination get the first slots, while nodes further from it get later ones. This is accomplished as follows. Based on periodic beacons [14], nodes build a table with the locations of their one-hop neighbors. Also, the previous hop's coordinates and expected radio range are included in the packet header. Each potential forwarder then executes the following procedure:

1) Define the set of expected forwarders $ES_{f,m}$ for message m, which is composed of the nodes that are both closer to the destination than the previous hop and within its radio range.
2) Build an array r from the set $ES_{f,m}$. Now sort r according to each node's distance to the destination. The index i at which a node appears in r is now its rank.
3) For each node in $ES_{f,m}$, assign it a forwarding slot $s = \left\lceil \frac{rank}{nps} \right\rceil$, where $rank$ is the node's rank and nps is the number of nodes per slot, a protocol parameter.

The last rule ensures that the first forwarding slot is taken by the node providing the most forwarding progress. The nps parameter controls a tradeoff between replication and latency: if more nodes are allowed per slot, the expected latency decreases while replication increases. Also note that nodes with ranks larger than the limit number of forwarders n refrain from forwarding to avoid excessive replication.

Let us use Figure 2 to go through an example. For simplicity, assume that the forwarding zones are defined as pictured, that each node within a zone has all the other nodes in the same zone in their neighbor table, and that each node gets its own forwarding slot ($nps = 1$). Consider, as an example, that in the first hop the set of nodes that receive the packet is $AS_{f,m} = \{a, b, d\}$. Note that these nodes do not know that c lost the packet, so they will include it in their ranking, making $ES_{f,m} = \{a, b, c, d\}$. Ordering the nodes according to their distance to the destination, every node will reach the same ranking $r = [d, c, b, a]$. Now, node d will the assigned the 1^{st} forwarding slot and c, b and a the 2^{nd}, 3^{rd} and 4^{th} slots, respectively. Realizing that it was assigned the 1^{st} slot, node d will immediately forward the packet. Nodes a and b will then overhear d's packet and cancel their own forwardings, avoiding any duplication.

Note that the algorithm is robust regarding small variations in rankings calculated by different nodes because forwarders in the same slot will still backoff at the MAC layer. Also, GPS errors are not critical to the protocol's operation. Their effect is limited to generating sub-optimal rankings.

IV. Benchmark protocols

A. Neighbor-based approach

We compare DAZL with a traditional neighbor-based protocol that follows a geographic routing approach. The node holding the packet leverages local neighborhood knowledge, acquired through periodic beaconing, to choose a next hop before sending the packet. As mentioned earlier, picking a next hop involves a difficult tradeoff between delivery rate and distance.

We implemented a protocol that uses a conservative algorithm based on a metric that combines both forward progress and reliability. Specifically, we choose the node that is closest to providing 50% of the forward progress given by the neighbor closest to the destination. For example, a node with three neighbors, a, b and c at 200, 100 and 50 m, respectively, will choose b as the relay. The value of 50% was taken from the results in Figure 3c, where the PDR of a single receiver remained under 80% in the second half of the communication range. We also evaluated neighbor-based forwarding using a greedy approach, which picks the neighbor closest to the destination, and a random approach, using a random neighbor, but their performance was consistently very poor.

B. Optimal oracle zone-based protocol

We also implemented an oracle zone-based protocol to allow us to understand how close DAZL gets to an idealized protocol with access to perfect and global information. The oracle-based protocol works as follows:

1) The currently selected node (initially the source) broadcasts the packet.
2) Every node in the network tells the oracle whether they have successfully received the packet or not.
3) Once the oracle has heard from all nodes it chooses the receiver closest to the destination to be the forwarder.

As this protocol cannot be implemented in practice, it is only considered in our simulation evaluation.

V. Experimental evaluation

Given the available resources, our experimental evaluation is limited to a small five-node setup. In the next section, we use simulations to evaluate DAZL in larger topologies.

A. Setup

Buildings are known to have a significant negative impact on VANET communication [2], [16]. We experimentally evaluate DAZL under such conditions using the setup in Figure 5. The source and destination cars are parked on two adjacent sides of a building and are unable to communicate directly. However, the three nodes close to the corner of the building can help by forwarding packets.

Each vehicle is equipped with a NEC LinkBird-MX [13] compatible with the IEEE 802.11p standard. Due to the platform's limitations, the protocols are implemented as an application running on a laptop connected to the Linkbird through ethernet. This means packets must travel across two protocol stacks and over the wire. This has two main implications for DAZL. First, overall latency will suffer. Second, overheard packets will take longer to process, increasing the likelihood of unnecessary replication. To mitigate this, we used longer 25 msec forwarding slots in our trials, giving the protocol more time to process overheard packets.

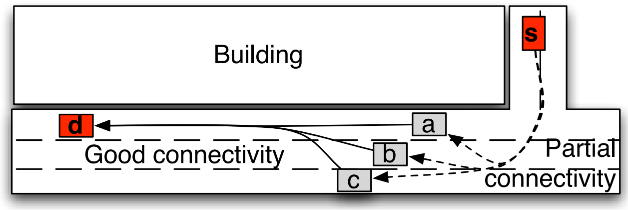


Fig. 5: Two-hop experimental topology.

Parameter	Value
Center frequency (MHz)	5900
Bandwidth (MHz)	10
Data rate (Mbps)	3
Tx power (setting, dBm)	5
Antenna gain (dBi)	6
Data packet size (Byte)	256
Beaconing frequency (Hz)	1

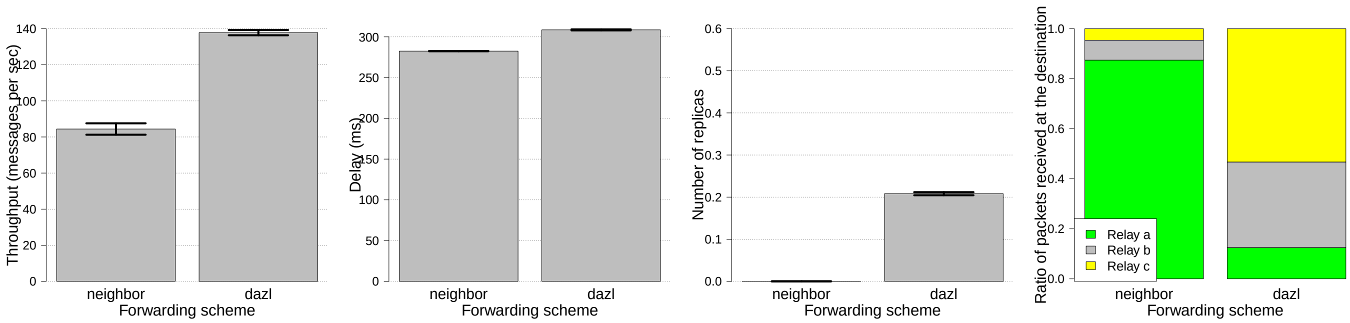
TABLE I: Linkbird configuration parameters.

The conservative neighbor-based protocol will pick the node closest to half of its radio range, which in this case is a. DAZL was configured to allow up to 3 forwarders ($n = 3$), one per forwarding slot ($nps = 1$). Retransmissions were disabled for all schemes, in order to highlight the differences in robustness between the protocols. The system configuration parameters are summarized in Table I. For each protocol, 100,000 messages were sent at a rate of 250 per second (mps).

B. Results

Figure 6a compares the mean throughput achieved by DAZL and neighbor-based forwarding in messages per second. The 95% confidence intervals are shown by means of ranges. Because the neighbor-based scheme chooses a single relay, its performance is severely affected by losses on the source-relay link. In fact, it only manages to get 84 mps to the destination, 33% of the source rate. DAZL, on the other hand, does not rely on any single node. It is able to leverage multiple relays and separate them into different forwarding slots. This results in a throughput improvement of 63% to 137 mps.

Figure 6b shows the mean end-to-end latency for the two protocols. Because of the platform limitations, the absolute values are larger than they would be in a production environment. In relative terms we see a delay increase of around 25 msec when moving from neighbor- to zone-based forwarding. This is due to the latency introduced by slotting. In a production version, the latencies would be a lot lower: the protocol stack would be implemented by a single device, allowing for much shorter slots, e.g. a few hundred μs.



(a) Throughput (b) End-to-end latency (c) Number of replicas (d) Relay diversity

Fig. 6: Experimental performance results.

Figure 6c shows the mean number of replicas observed at the destination. Because retransmissions due to message losses were disabled, the neighbor-based protocol generated no replication. DAZL generated, on average, 20% replication. This number is artificially high because of the radio set up on the Linkbirds. When a node overhears a forwarded packet from another relay, it should refrain from forwarding. This is done by having the forwarding protocol tell the MAC to drop the now redundant message from its transmit queue. We were however unable to alter the MAC layer on the Linkbirds to do this, which results in duplicate packets. Production systems will use a single stack implementation of DAZL, which does not have this problem. Our simulator also implements forwarding cancellation correctly.

Finally we look at vehicle diversity: from all the messages reaching the destination, we compute the ratio coming from each of the relays and plot it in Figure 6d. The conservative neighbor-based scheme chooses a roughly 90% of the time. The 10% attributed to relays b and c is due to node a occasionally loosing connectivity with the source.

DAZL assigns slots based on the distance to the destination so node c gets the 1^{st} slot, b the 2^{nd} and a the 3^{rd}. Node c has the highest priority and accounts for around 50% of the packets at the destination. Node b accounts for 40% and node a 10%, values that are consistent with their slot assignments.

These results highlight the benefits of the DAZL scheme, even when only a few forwarders are available.

VI. Simulation Evaluation

We use the ns3 simulator with 802.11p support for a larger scale evaluation. The simulation parameters are presented in Table II. Nodes are placed on a 1 Km-long road according to an exponential distribution representative of an actual highway [11]. In our analysis we used average inter-vehicle distances ranging from 80 (sparse but connected) to 10 meters (traffic jam). A sender at one end of the road sends 322 byte data packets at a rate of 200 per second to a destination at the other end. The maximum number of retransmissions was set to two. DAZL forwarding slots are set to 2 ms. The number of forwarders was limited to 7 and the expected range set to 150 m. Neighbor discovery was performed using 1 Hz beacons. Results are averaged over five 60 second runs with different random seeds.

Parameter	Value
Center frequency (MHz)	5900
Bandwidth (MHz)	10
Data rate (Mbps)	3
Tx power (dBm)	16
Fading model	Nakagami, m=1.5

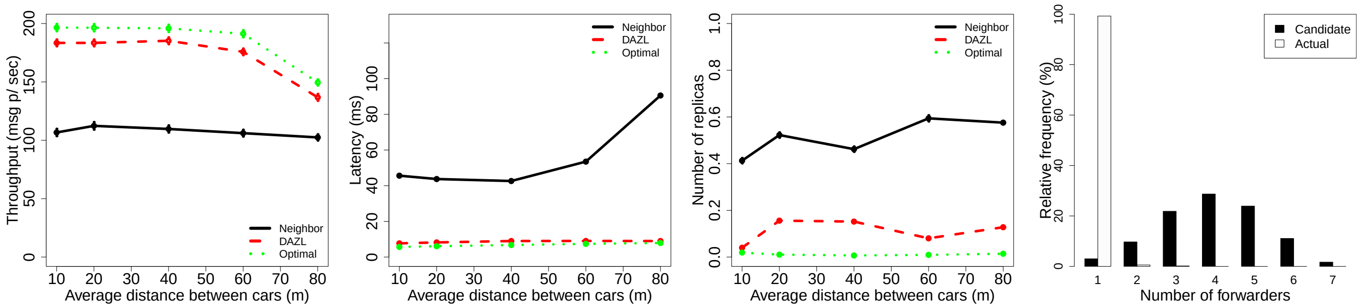
TABLE II: ns3 configuration parameters.

A. Results

Figure 7 compares DAZL's performance with that of the conservative neighbor-based and oracle zone-based protocols described in Section IV. The vertical lines and hash marks represent the 95% confidence intervals, where available.

Figure 7a shows the throughput for the three schemes. The neighbor-based protocol hovers around 110 mps (55% of the source rate). This is the result of packets losses: 45% of the time the selected next-hop is unable to receive the message successfully. The oracle scheme, however, does not rely on any specific node: it works as long as at least one node, any node, receives the packet. Due to this it gets very close to the source rate of 200 mps. DAZL goes up to 185 mps, which is within 10% of the oracle protocol. The reason is that it can use up to 7 potential forwarders. Also, the fact that DAZL's throughput does not decrease at higher densities shows that slotting and the limited number of forwarders are effective in preventing excessive contention and losses.

Figure 7b shows end-to-end latency for all protocols. DAZL performs very similarly to the oracle protocol. Both have latencies below 10 msec and the results are fairly consistent across densities. This indicates that the small delay introduced by DAZL through slotting does not impact overall latency significantly. Also, DAZL's built-in redundancy results in significantly lower latencies compared with the neighbor-based protocol. The reason is that neighbor-based forwarding results in more packets losses, and thus in a lot of retransmissions. These are very costly not only because of the additional



(a) Throughput

(b) Latency

(c) Replication

(d) Candidate vs actual forwarders in DAZL (10 m inter-vehicle spacing)

Fig. 7: Simulation results; DAZL is compared against a neighbor-based protocol and an idealized oracle protocol.

transmission time, but also because the node has to wait before finally timing out and retransmitting.

We now turn our attention to the number of replicas observed at the destination—Figure 7c. As expected, the oracle protocol does not generate any replicas. On the other hand, the neighbor-based scheme generates a significant amount of replication of up to 60% due to losses. Because the packet delivery ratio between previous hop and forwarder is not perfect, sometimes the former doesn't hear the forwarding done by the latter, leading to spurious retransmissions.

DAZL generates replication when the potential forwarders fail to hear each other. Replication is well contained however, never going beyond 18%. This is due to the employed cancelation mechanism, whose operation can be observed in Figure 7d. This graph compares the number of potential forwarders with the number of actual forwarders for the 10 m inter-vehicle spacing scenario. Here we can observe that 97% of the time, there are two or more potential forwarders, a situation that could lead to replication. However, 99% of the time there is only one actual forwarder, which proves the effectiveness of our scheme.

The results here presented clearly demonstrate the advantage of zone-based forwarding in vehicular wireless networks. DAZL performs almost as well as the oracle protocol by using only local information and a distributed algorithm.

VII. Related work

Our work builds upon a few key results within the field of wireless networks. The first is the observation that vehicular networks suffer from the gray-zone phenomenon, a problem that existing vehicular protocols do not address. Second, the idea that radio diversity can be used to opportunistically tackle unreliable channels has been proposed in the context of WLANs and mesh networks. DAZL applies these concepts to the vehicular network context.

The existence of a large gray-zone of partial connectivity in VANETs was first pointed out by Bai et al [3]. In their experiments they found the probability of having an intermediate packet delivery rate between 20 and 80% to be 50%.

Kaul et al [17] studied the effect of multi-radio diversity using antennas placed in different parts of a vehicle. In their experiments they reported a 10-15% packet error rate reduction by adding a second radio. Given that the antennas were placed very close to each other, this can be seen as a lower bound on the benefits of radio diversity on vehicular environments.

Most VANET routing protocols do not use diversity. Instead, they focus on a neighbor-based strategy of choosing a single relay per hop, differing mostly in the metric used for relay selection. GPSR [10], A-STAR [4] and Gytar [5] choose the neighbor closest to the destination, a risky choice given the gray-zone phenomenon present in VANETs. ACAR [12] uses a modified Expected Transmission Count (ETX) metric [18] that tries to minimize the end-to-end error probability. This is a good improvement but still has a single point of failure.

BLR [19] and CBF [20] are two VANET protocols where forwarding decisions are made on the receiver side like in DAZL. However, they do not establish a strict prioritization order and are therefore susceptible to replication and unable to limit the number of forwarders to reduce contention in high density environments. DOT [21], establishes a prioritization like DAZL, but does not limit the number of forwarders.

Diversity has previously been used in other contexts to recover from losses. Multi-Radio Diversity (MDR) [8] is a low-level scheme for WLANs where corrupt frames received at different APs are combined in a central node to try and extract a correct frame from the multiple corrupt copies. Unlike DAZL, this scheme requires a shared channel to a central node, rendering it unsuitable for vehicular use.

Opportunistic routing has also been explored in the context of mesh networks, with the most prominent protocols being ExOR [6] and MORE [22]. Both leverage diversity by using multiple relays and both assume network-wide knowledge of channel quality between every pair of neighbors, which is reasonable for mesh networks but does not hold in VANETs.

PRO [7] is a scheme for infrastructure WLANs that shares DAZL's distributed and opportunistic flavor. In PRO, when a transmission fails, relays that have a good RSSI towards the destination opportunistically retransmit the packet on behalf of the source, increasing reliability. PRO requires nodes to learn the RSSI between all sources and destinations. While this is feasible in WLANs, all nodes in VANETs can be senders and receivers, plus channels are very dynamic. This is why DAZL ranks relays based on distance rather than RSSI.

The idea of avoiding MAC layer contention by reducing the number of candidate transmitters first appeared as an answer to the broadcast storm problem [23]. Some schemes, such as SAPF [24] and P-persistence [25] use a simple probabilistic rule to control the number of forwarders, without prioritization. Slotting for spreading forwarders in time was introduced by Linda et al [26] and later used in Slotted p-persistence [25]. These approaches use a fixed number of slots and therefore can not adapt to different node densities. Adaptive slotting based on workload and density has been proposed in some TDMA-based MAC protocols [27], [28], which are not compatible with 802.11p.

VIII. Conclusions

We presented DAZL, a zone-based forwarding scheme that lets any node in a geographic region forward a packet towards a destination. The protocol is entirely distributed and relies only on local information. In contrast to traditional neighbor-based protocols, zone-based forwarding has built-in redundancy that makes it robust with respect to the unpredictable packet delivery rates found in vehicular networks. To reduce contention in high density scenarios, DAZL uses a slot-based algorithm that adapts the forwarding zone's size according to the local node density. Moreover, forwarders are prioritized to maximize hop length. This approach offers a good balance between high throughput and low latency and replication.

We evaluated DAZL using both experiments and simulations. We found that DAZL outperforms neighbor-based schemes for all node densities, with improvements of around 60% in throughput. Furthermore, DAZL's throughput is up to 90% of what could be achieved with an oracle protocol that knows what packets are received and lost, something that cannot be implemented in practice.

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