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Speed and Position Aware Dynamic Routing for Emergency Message Dissemination in VANETs

RUIYAN HAN[1], JINGLUN SHI[1], QUANSHENG GUAN[1], (Senior Member, IEEE), FARHAD BANOORI[1], AND WEIQIANG SHEN[2], (Member, IEEE)
[1]School of Electronic and Information Engineering, South China University of Technology, Guangzhou 510641, China
[2]School of Electronic and Information, Guangdong Polytechnic Normal University, Guangzhou 510665, China

Corresponding author: Jinglun Shi (shijl@scut.edu.cn)

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ABSTRACT Vehicular Ad hoc Networks (VANETs) can help reduce traffic-related accidents by broadcasting Emergency Messages (EMs) in advance between vehicles. Due to the high-speed mobility of VANETs and attenuation of the wireless signal, reliable and fast transmission of EMs is a challenging task. Such as the chosen next-hop vehicle may have driven away from the neighborhood of the sender before receiving the EM, and rerouting may increase the delay when the EMs encounter transmission failure. To this end, we propose a Speed and Position aware Dynamic Routing (SPDR) for EM dissemination in VANETs. First, we introduce a speed metric dynamic greedy routing to provide a dynamic hop-by-hop rebroadcast of the EM. SPDR dynamically shrinks the Routing Decision Area (RDA) range based on the velocity variance of candidate neighbors and prioritizes the farthest vehicle in the shrunk RDA as the optimal next-hop, enhancing the reliable transmission of EMs. Then, we present a collaborative forwarding strategy to enable candidate neighbors to collaborate in communication. In case of transmission failure, SPDR elects the candidate vehicle close to the destination as the forwarder to reduce rerouting. Simulations in a practical motorway scenario using NS-2 and VanetMobiSim show that SPDR outperforms the existing protocols in terms of message delivery ratio, network throughput, and average dissemination delay.

INDEX TERMS Vehicular ad hoc networks (VANETs), dynamic routing, emergency message (EM), next-hop selection, velocity variance.

I. INTRODUCTION

Traffic accidents result in thousands of deaths every year, more than any other fatal disease or natural disaster. Intelligent Transportation System (ITS) has a significant capacity to improve traffic safety. In light of that, Vehicular Ad hoc Networks (VANETs) are linked with ITS to improve road safety, optimize traffic efficiency, and provide infotainment services via Vehicle-to-Vehicle (V2V) and Vehicle-to-Roadside (V2R) communications [1]–[3]. Moving vehicles can quickly and accurately gather real-time road traffic information, share it, and concurrently alert neighboring vehicles of the potential hazardous event quickly once the traffic accident has been detected. Thus, VANETs are considered a promising technology to support safety-related communication services [4].

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Suppose the vehicle detects any abnormalities in the road. In that case, it immediately generates and broadcasts the Emergency Message (EM) to all vehicles within a specific geographic area so that approaching vehicles can take practical actions in advance to avoid secondary traffic crashes. Due to the limited transmission range of vehicles, EMs have to be transmitted to vehicles far away from the source vehicle through multiple hops. Studies show that about 60% of road accidents could be prevented if drivers were notified at least half a second before a collision [5]. Therefore, the multi-hop routing for the dissemination of EMs containing life-critical information should guarantee the Quality of Services (QoS) such as high reliability and low latency [6], [7].

Multi-hop broadcast communications typically cause the broadcast storm problem [8] and unreliable transmissions. Particularly in high-density networks, redundant message transmissions result in severe packet collisions and channel contention [9]. To tacke this issue, many schemes have been proposed in the literature [10]–[23] to select a subset of neighbor vehicles to relay EMs to reduce retransmissions. The wait-time-based schemes in [10]–[15] allow Candidate Neighbors (CNs) to adjust their wait time in inverse proportion to their distances from the sender. Usually, the most distant neighbor with the greatest distance has the shortest wait time, and it will retransmit the EM when its wait time expires. However, the accumulated wait time per hop can lead to extended dissemination delay.

To minimize the delay for rebroadcasts, the sender-based schemes in [16]–[19] specify the next forwarder to rebroadcast EMs without additional wait time. They tend to select the farthest neighbor from the sender as the next-hop relay based on the information exchanges among neighbors for fast propagation. However, due to the high speed of vehicles, the selected relay vehicle may move outside the communication range of the sender before it receives the message [24], or the sender may use outdated neighbor information for routing decisions, resulting in forwarding failure. On the other hand, the farthest relay vehicles may not receive EMs owing to wireless attenuation in the schemes mentioned above, which significantly degrades reliability and increases the delay due to retransmissions.

To ensure reliable transmission and timeliness, we propose a Speed and Position aware Dynamic Routing (SPDR) to disseminate EMs on the motorway, which consists of speed metric dynamic greedy routing and collaborative forwarding strategy. The main contributions are summarized below.

- *Speed metric dynamic greedy routing*: SPDR combines mobility to appropriately shrink the Routing Decision Area (RDA) range per forwarding. It dynamically estimates the RDA range using the velocity variance of CNs, then prioritizes the farthest vehicle in the shrunk RDA as the relay to immediately rebroadcast EMs. The EMs are forwarded hop-by-hop from the source vehicle to the destination. SPDR can effectively prevent the chosen forwarder from leaving the reception range of the sender during message forwarding.
- *Collaborative forwarding strategy*: We allocate the wait time for candidates receiving new EMs and enable them to start the waiting process during message forwarding. Once forwarding failure occurs, SPDR elects the candidate close to the destination as a forwarder because it waits less time, thus reducing rerouting and delay.

The remainder of this paper is organized as follows. Section II presents the related works, and Section III presents the network model. We propose dynamic routing for EM dissemination in Section IV. Later simulation results are shown in Section V. Finally, Section VI concludes this paper.

II. RELATED WORKS

This section discusses existing broadcast protocols used to support safety-related applications in VANETs. Flooding represents the simplest broadcast scheme available, which can disseminate EMs to all vehicles within the restricted area [25]. However, flooding is not suitable for routing mission-critical EMs in VANETs, which are prone to high packet collisions, high data redundancy, and even the broadcast storm problem. Reducing the redundant retransmissions is an efficient approach to mitigate message collisions and the storm problem [14]. Some researchers have selected a set of relay vehicles to rebroadcast EMs via multi-hop communications [10]–[23]. In addition, probabilistic flooding [26] and constructing tree topology [27], [28] have also been adopted as alternative schemes to mitigate the redundant message problem in VANETs.

From the perspective of selecting the next-hop relay, the broadcast routing protocols for disseminating EMs are mainly classified into cluster-based, receiver-based, and sender-based. In disseminating EMs, the cluster-based protocol in [20]–[23] divided the network into several clusters. Each cluster selected a cluster head to be responsible for intra-cluster management and dispersing the message to other clusters. Moreover, the cluster-based Medium Access Control (MAC) protocol can improve the reliability of transmission within the desired QoS constraints [29]–[31]. The clustering technique can reduce unnecessary retransmissions of the EMs when they are broadcast, but it is vulnerable to suffer from instability because of the high mobility of vehicles. For that, research works in [32], [33] used relative speed between vehicles as a criterion for cluster head selection to construct the stable cluster. However, due to the highly dynamic nature of VANETs, vehicles frequently join and leave the cluster, which leads to extra maintenance overhead and degrades the reliable transmission of messages [34].

The receiver-based protocols in [10]–[15] forced the receivers to wait based on the wait-time forwarding mechanism before rebroadcasting EMs, in which the receiver with the minimum wait time would resend the message. The wait-time forwarding mechanism was first introduced to VANETs in [35]. It was later extended to solve the broadcast storm in [36] for the EM dissemination in vehicular networks. Research works in [10], [11] scheduled the farthest forwarder candidate to access the channel preferentially to rebroadcast the EM. The work in [12] determined the vehicle farthest from the source to forward the EM after its waiting period was over. The reference [13] adopted the trinary partitioning mechanism to allow vehicles as far as possible in the farthest sector from the sender to perform forwarding. The methods proposed in [14], [15] assigned deferral time for receiving vehicles using predefined functions. Specifically, the vehicle farthest away from the sender is set the shortest wait time to achieve rapid propagation. However, the complex wireless channels environment leads to signal attenuation, resulting in the most distant vehicle not receiving the message. It may indicate that the vehicle whose wait timer expired first is not the closest to the destination, increasing the delay.

Rather than making the routing decisions at the receiver, the sender-based broadcast protocols in [16]–[19] appointed one or more neighbors farthest from the sender as the relay vehicles to spread the message speedily and reliably. The reference [17] adopted the n-way search to find the farthest neighbor vehicle to broadcast EMs in VANETs. The reference [18] specified the farthest neighbor vehicle on the chosen path to forward emergency data. The work in [19] selected the farthest neighbor node as the relay using the received beacons. The schemes for choosing the furthest vehicle for rapidly disseminating EMs come from the idea of Greedy Forwarding (GF) routing. The GF [37] selects the node closest to the destination node from the neighbor list of the sender as the next-hop forwarder to quickly disseminate EMs in VANETs [38]. However, due to high mobility, the furthest relay vehicle may not be the neighbor of the sender before receiving the EM [24], [39]. Additionally, the forwarder may use expired neighbor list for routing decisions, because it is difficult to keep real-time neighbor information in highly dynamic VANETs.

For these reasons, they may result in forwarding failure, which enhances the packet loss rate. Cooperation communication can compensate for EMs reception failure with the help of neighbor vehicles [40]. As a result, the design of SPDR has jointly considered mobility of vehicles to improve the reliability of transmission and collaborative communication to handle forwarding failure.

III. NETWORK MODEL

We envisage a VANET without roadside infrastructure support in a motorway environment. The VANET consists of N moving vehicles randomly deployed on the road, two lanes, an intersection as a U-turn point, and a fixed exit at the roadside, as shown in Fig. 1. We concentrate on the motorway scenario since vehicles can lose considerable time in traffic jams when they miss the exit closest to the crashed vehicle. Vehicles can move in two opposite directions on multi-lanes and turn right/left at the intersection; Moreover, they can directly communicate with each other via IEEE 802.11p network communication interfaces. The on-board unit installed in vehicles is responsible for detecting the traffic conditions. Once the vehicle detects an accident, it generates the corresponding EMs and periodically broadcasts to neighboring vehicles to warn of the potential hazards. We assume that vehicles can obtain their positions and speed through global positioning systems and wheel speed sensors, respectively. The system supports vehicles to disseminate EMs via multi-hop in VANETs.

Furthermore, we divide the motorway into two sections according to the exit location in our network scenario considered. The exit is a branch of the highway, which can divert traffic to avoid traffic gridlock. It plays as the destination in our simulations. We define the destination zone (i.e., section B in Fig. 1) as the rectangular area after the exit. The Abnormal Vehicle (AV) periodically broadcasts EMs, and the EMs disperse towards the destination zone. The vehicles located in lane 1 on section A must receive the EMs so that they can avoid the potential crash accident. Our SPDR aims to ensure that all vehicles in the destination zone receive the EMs as soon as possible, which allows drivers to change their route to the exit or the U-turn intersection to avoid congestion caused by accidents. Therefore, the EMs in section A must be forwarded reliably and delivered to the destination zone promptly on time.

For convenience, the main notations used in our model are summarized in Table 1.

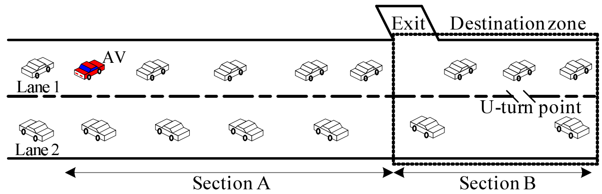


FIGURE 1. Network model.

TABLE 1. Notations used in the model.

Notations	Description
$D(i, d, t)$	The Euclidean distance between node i and destinatin node d at time t.
R	Communication range.
R_{RDA}	The RDA range.
$R_{RDA_{\max}}$	Maximum range of RDA.
$R_{RDA_{\min}}$	Minimum range of RDA.
R_C	The range of the critical area.
$R_{C_{\max}}$	Maximum range of the critical area.
$R_{C_{\min}}$	Minimum range of the critical area.
N_R	The neighbors located in R.
N_{RDA}	The neighbors located in the RDA.
t_r	The transmission delay for the EM from vehicla a to vehicle b.
S_i	The distance that vehicle i travels from the location of i to the location of i' within t_r.
S_{ab}	The distance from the location of a' to the location of b.
v_a, v_b	Speed of vehicle a and vehicle b within t_r, respectively.
$\triangle v$, $\triangle v'$	The relative speed of vehicle a and vehicle b, and $\triangle v = \lvert v_b - v_a \rvert$, $\triangle v' = \lvert v_b + v_a \rvert$.
$\triangle v_{\max}$, $\triangle v'_{\max}$	Maximum value of $\triangle v$ and $\triangle v'$, respectively.
$\triangle v_{\min}$, $\triangle v'_{\min}$	Minimum value of $\triangle v$ and $\triangle v'$, respectively.
σ_v	Velocity variance of the FNs.
$WT_{\max}$	The maximum wait time from receiving the message to sending it out.
wt_{min}	The minimal wait time.

IV. DYNAMIC ROUTING FOR EM DISSEMINATION

This section presents the implementation of our proposed dynamic routing for EM dissemination on the motorway, which entails speed metric dynamic greedy routing, collaborative forwarding strategy, and exchanges of neighboring locations and speed.

A. SPEED METRIC DYNAMIC GREEDY ROUTING

Given the uneven distribution of neighboring vehicles, we define neighbors located in the near area between the sender and the destination zone as Forward Neighbors (FNs) and Backward Neighbors (BNs) situated in the distant region between the sender and the destination zone. Our speed metric dynamic greedy routing selects the next-hop relay from the FNs to reduce delay. It consists of two steps, which include dynamic setting the RDA range and routing decision.

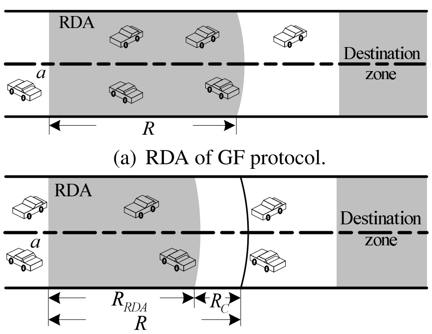
1) DYNAMIC SETTING THE RDA RANGE

The packet is marked with its destination location by its originator in GF. The traditional GF algorithm uses the distance difference to determine the next-hop node b_{opt} at time t, i.e.,

$$b_{opt}(t) = \arg\max_{\{b \in N_R\}} [D(a,d,t) - D(b,d,t)], \tag{1}$$

where $D(a,d,t)$ denotes the distance between sender a and the destination d at time t; $D(b,d,t)$ denotes the distance between the next-hop candidate node b and the destination d at time t; N_R denotes the neighbors located in the communication range R. It means that node b closest to the destination will be selected as the next forwarder.

Since the RDA range in GF is the same as R, as shown in Fig. 2(a), the next-hop selection strategy in (1) tends to select the neighbor located at the communication boundary of the sender as the next forwarder. However, due to high mobility, the chosen forwarder may have driven away from the transmission range of the sender during forwarding the EM, resulting in communication link interruption and forwarding failure. For the avoidance of this phenomenon, along the message dissemination direction, our SPDR appropriately shrinks the RDA range based on the mobility of vehicles, as shown in Fig. 2(b), which enhances the stability of the communication link between the sender and the next-hop.



(a) RDA of GF protocol.

(b) RDA of our proposed SPDR.

FIGURE 2. Comparison of the RDA in both protocols.

Additionally, if the RDA range is set extensively large, once the selected relay vehicle moves too fast, it may head out of the neighborhood of the sender during communication. This action cannot efficiently ensure reliable message forwarding. Correspondingly, suppose the RDA range is set extensively small. It is possible to forward messages reliably, but this leads to an excessive increase in hops, increasing the probability of message loss and delay. Therefore, it is obligatory to dynamically set the RDA range hop-by-hop according to the speed of dynamic FNs.

To reasonably set the RDA range per hop, we define the transmission delay for the EM from vehicle a to vehicle b as t_r, and the critical area R_C $\left(R_C \in \left[R_{C_{\max}}, R_{C_{\min}}\right]\right)$ that the distance traveled by the selected next forwarder happens to reach the communication border of the sender within t_r, as shown in Fig. 2(b). Let b_i $(i \in [1,\ N])$ denote the set of FNs, and R_{RDA} denote the RDA range, then R_{RDA} is computed as $R_{RDA} = R - R_C$. Moreover, we define the moving direction of the vehicle headed towards the destination zone as the positive direction, which is denoted by the symbol $+$; otherwise, it is recorded as $-$. Correspondingly, we investigate and compute R_{RDA} in the following three cases, as shown below:

Case 1: When sender a and b_i are all $-$ as shown in Fig. 3, the chosen next forwarder is unlikely to drive outside the communication area of the sender within t_r. In this case, there is no need to shrink R_{RDA}, then $R_{RDA} = R$.

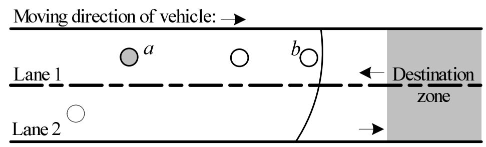


FIGURE 3. Network scenario 1.

Case 2: When sender a and b_i are all $+$ as shown in Fig. 4, we assume that sender a has a neighbor b moving to its communication boundary, and vehicle a and vehicle b happen to be in a critical connection state within t_r. Let S_a denote the distance that sender a travels from the location of a to the location of a' within t_r, S_b denote the distance that the neighbor b travels from the location of b to the location of b' within t_r. Since t_r is very small, the vehicle moves at almost constant speed in t_r. Then we can acquire the displacement that vehicle a covered at speed v_a within t_r and vehicle b covered at speed v_b within t_r, i.e., $S_a = v_a \cdot t_r$ and $S_b = v_b \cdot t_r$ respectively.

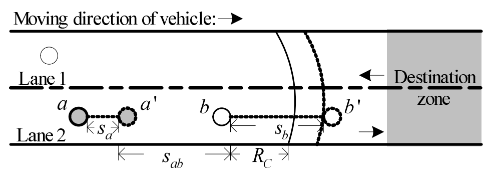


FIGURE 4. Network scenario 2.

The communication range of the moving vehicles remains unchanged. According to Fig. 4, we can rewrite R as follows,

$$S_a + S_{ab} + R_C = R \tag{2}$$

$$S_{ab} + S_b = R \tag{3}$$

where S_{ab} denotes the distance from the location of a' to the location of b. Substituting S_a and S_b into (2) and (3) respectively, we have

$$|v_b - v_a| \cdot t_r = \triangle v \cdot t_r = R_C \tag{4}$$

where $\triangle v$ denotes the relative speed of vehicle a and vehicle b, and $\triangle v = |v_b - v_a|$. Since vehicles move at various speed, subsequently, $R_{C_{\max}} = \triangle v_{\max} \cdot t_r$ and $R_{C_{\min}} = \triangle v_{\min} \cdot t_r$.

According to $R_{C_{\max}}$ and $R_{C_{\min}}$, we can obtain:

$$R_{RDA_{\max}} = R - R_{C_{\min}} \tag{5}$$

$$R_{RDA_{\min}} = R - R_{C_{\max}} \tag{6}$$

where $R_{RDA_{\max}}$ denotes the maximum range of RDA, $R_{RDA_{\min}}$ denotes the minimum range of RDA.

The velocity variance can reflect the speed fluctuations of the sender's neighbors. If the velocity variance of the FNs is greater, we should reduce R_{RDA} because the speed of the FNs fluctuates wildly. If the velocity variance of the FNs is lower, we should increase R_{RDA} because the speed fluctuation of the FNs is relatively tiny. Hence, we define R_{RDA} as follows,

$$R_{RDA} = R_{RDA_{\max}} - \sigma_v \cdot \left(R_{RDA_{\max}} - R_{RDA_{\min}}\right) \tag{7}$$

where σ_v denotes velocity variance of the FNs. We can see from (7) that parameter σ_v is the critical factor affecting R_{RDA}.

Substituting (5) and (6) into (7), we get the following R_{RDA} in case 2,

$$R_{RDA} = R - \triangle v_{\min} \cdot t_r - \sigma_v \cdot (\triangle v_{\max} - \triangle v_{\min}) \cdot t_r \tag{8}$$

Case 3: When sender a is $-$ and all b_i are $+$ as shown in Fig. 5, we assume that sender a has a candidate b moving to its communication boundary, and vehicle a and vehicle b happen to be in a critical connection state within t_r.

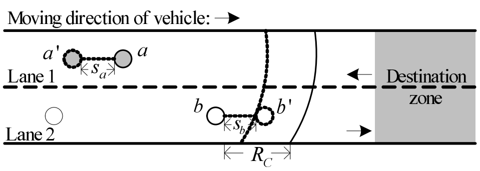


FIGURE 5. Network scenario 3.

According to Fig. 5, we can rewrite R as follows,

$$S_a + (R - R_C) + S_b = R \tag{9}$$

Substituting S_a and S_b into (9), we have

$$|v_a + v_b| \cdot t_r = \triangle v' \cdot t_r = R_C \tag{10}$$

where $\triangle v'$ denotes the relative speed of vehicle a and vehicle b, and $\triangle v' = |v_b + v_a|$. In this case, we can acquire $R_{C_{\max}} = \triangle v'_{\max} \cdot t_r$ and $R_{C_{\min}} = \triangle v'_{\min} \cdot t_r$.

Then, substitute $R_{C_{\max}}$ and $R_{C_{\min}}$ into (5) and (6), respectively. Based on (7), we derive the following R_{RDA} in case 3,

$$R_{RDA} = R - \triangle v'_{\min} \cdot t_r - \sigma_v \cdot \left(\triangle v'_{\max} - \triangle v'_{\min}\right) \cdot t_r \tag{11}$$

Since $|v_a + v_b| \geq |v_a - v_b|$, then $\triangle v'_{\max} - \triangle v'_{\min} \geq \triangle v_{\max} - \triangle v_{\min}$ and $\triangle v'_{\min} \geq \triangle v_{\min}$. Hence, (11) increases more hop progress of the EM than (8). Consequently, when vehicles exist in two-way lanes, we can employ (8) to calculate the R_{RDA} to reduce propagation delay and can use (11) to further enhance reliable forwarding. From the above analysis, we have

$$R_{RDA} = \begin{cases} R, \ if \ case \ 1. \\ R - \triangle v_{\min} \cdot t_r - \sigma_v \cdot (\triangle v_{\max} - \triangle v_{\min}) \cdot t_r, \ if \ case \ 2. \\ R - \triangle v'_{\min} \cdot t_r - \sigma_v \cdot \left(\triangle v'_{\max} - \triangle v'_{\min}\right) \cdot t_r, \ if \ case \ 3. \end{cases} \tag{12}$$

We can adopt (12) to dynamically set R_{RDA} for each forwarding according to different service requirements.

2) ROUTING DECISION

After our SPDR calculates R_{RDA} using (8), it will make the routing decision to select the next-hop to rebroadcast EMs. SPDR schedules the optimal b_{opt} at time t using the following criterion:

$$b_{opt}(t) = \arg \max_{\{b \in N_{RDA}\}} [D(a, d, t) - D(b, d, t)] \tag{13}$$

where N_{RDA} denotes the neighbors located in the RDA. It states clearly that SPDR will schedule the fartheset neighbor in the shrunk RDA as the next forwarder.

In addition, SPDR adopts the store-carry-forward mechanism when no reachable neighbor is available. To prevent buffered messages from being carried all the time, we set up a carry timer for the message. Once a suitable next-hop can be found before its carry timer expires, the message is forwarded and removed from the cache. Otherwise, the message is discarded.

B. COLLABORATIVE FORWARDING STRATEGY

Untimely updated neighbor information causes difficulties in finding a suitable next-hop for EM forwarding, and an unstable wireless channel leads to wireless signal attenuation. These stumbling blocks may lead to forwarding failure and retransmission. However, due to the dynamic changes of neighbors, the sender needs to recalculate the next forwarder for retransmission, which increases the computational overhead.Once the sender heads away from the destination zone, this will increase additional dissemination delay. To reduce rerouting, our SPDR allows FNs to participate in rebroadcast to cope with forwarding failure collaboratively, improving the message reception rate.

In our method, the sender calculates the rebroadcast wait time for selected next-hop using (14) at time t. We define the rebroadcast wait time of the selected forwarder as the minimal wait time wt_{min}, and let the EM carry the wt_{min} in its packet header. The FNs b_i receiving the message use (14) to calculate their rebroadcast wait time wt_i respectively. If all FNs start their wait timer based on their wt_i, this would complicate protocol management or lead to redundant broadcasts in high-density networks. FNs satisfying $wt_i \leq wt_{\min}$ may not receive the broadcast messages due to the attenuation of the wireless signal. To reduce unnecessary redundant broadcasts, we start the wait timers for CNs that satisfy $wt_i - wt_{\min} \leq \Delta t$ (Δt is a tiny constant) and begin their wait process.

$$wt(b, t) = WT_{\max} - \frac{D(a, d, t)}{R} \cdot WT_{\max}, D(a, d, t) \in (0, R) \tag{14}$$

where $WT_{\max}$ denotes the maximum wait time from receiving the message to sending it out.

If the CN receives the EM from the selected next forwarder before its timer expires, then this is a successful transmission. Otherwise, this is a failed transmission. Once the sender encounters the transmission failure, its CNs will not receive the message from the next forwarder until their wait timers expire. Then the corresponding timers of CNs expire in turn according to the order in which they receive messages. The wait timer of the CN close to the destination will expire first because it has the shortest wait time. So it will become the elected forwarder and suppress the wait timers of other CNs. To reduce the transmission delay of EMs per hop, we assign the highest forwarding priority to the selected/elected forwarder. They shall directly serve as the relay when receiving the EMs.

When the sender successively receives the same EM more than once, it discards the EM received afterward to achieve forwarding timely. Since the CN may receive multiple EMs from different senders during the rebroadcast wait period, each vehicle maintains a routing record list for recording the EMs it has received. Each entry in the list includes sender ID, next forwarder ID, EM's sequence number, wait time and wt_{min}. On receiving an EM, the vehicle will verify whether it is the selected/elected forwarder by checking its ID. If it is the next forwarder, it will rebroadcast the EM to its neighbors at once. Otherwise, it will judge whether it is an FN or a BN using the distance to the sender and then start/stop the wait timer or discard the EM. The detailed processing of the vehicle receiving the EM is summarized in Alg. 1.

If we set wt_i as the expiration time of corresponding timers, even though the EM is successfully forwarded, the CN with a short wait time may not have received the EM from the next forwarder when its timer expired. This occurs due to the inevitable network delay, which results in unnecessary elections for CNs. Therefore, we should set the expiration time of CNs' wait timers larger than their corresponding wt_i, which is set to t_r. Moreover, the expiration time of the sender's wait timer should be larger than that of CNs, including the round-trip transmission delay to the next forwarder and the transmission delay of elected forwarder caused by forwarding failure, which is set to $3t_r$.

Algorithm 1 Processing Algorithm at a Vehicle on Receiving an EM

```
if it is the selected/elected forwarder then
    Calculate the R_RDA;
    Select the next-hop in the shrunk RDA and calculate the wt_min;
    Rebroadcast the EM to all neighbors instantly.
end if
if it is an FN then
    Calculate its wt_i.
    if wt_i − wt_min ≤ △t then
        if there exists an entry then
            Update the entry;
        else
            Create a new entry in the routing record list;
        end if
        Start the wait timer of the EM.
    else
        Discard the EM.
    end if
end if
if it is a BN then
    Lookup whether there exists an entry of the EM;
    if there exists the entry then
        Stop the wait timer of the EM;
        Free the EM;
        Delete the entry.
    else
        Discard the EM.
    end if
end if
```

C. EXCHANGES OF NEIGHBORING LOCATIONS AND SPEED

SPDR requires neighboring locations, movement direction, and speed to calculate R_{RDA}, as shown in (12). Each vehicle uses a periodic beacon mechanism to broadcast its geographic location, movement direction, and velocity. The vehicle can then establish a neighbor table using the exchanged information from one-hop neighbors. The neighbor entry contains node ID, geographic location, movement direction, and speed. Moreover, the sender classifies its one-hop neighbor table into an FN table and a BN table according to the location information when it makes the routing decision for the next forwarder.

Each neighbor entry in a vehicle has a certain period of validity. However, some neighbors will inevitably leave the communication area of vehicles during the validity period. In this case, SPDR may use obsolete neighbors, leading to failed forwarding. The routing layer relies solely on the beaconing mechanism to detect the outdated neighbors. From another perspective, the MAC layer considers that a neighbor is inaccessible when the frame transmissions to that neighbor fail multiple times. Therefore, we allow the MAC layer to send feedback about the link failure to the routing layer and delete the corresponding entry from the neighbor table. It enables the routing layer to discover expired neighbors in time without waiting for the expiration of the neighbor entry, thus reducing packet losses. As SPDR does not rely on path calculation, deleting a neighbor entry does not affect the end-to-end forwarding. Any changes of a neighbor entry will trigger the reconfiguration by the algorithm described in Section IV-A.

V. SIMULATION RESULTS

In this section, we use VanetMobiSim and NS-2 on the Linux platform to simulate the performance of our proposed SPDR in VANETs.

A. SIMULATION ENVIRONMENT

The VanetMobiSim software is used for road traffic simulation. We perform our SPDR in NS-2 according to the trace file of moving vehicles generated by VanetMobiSim. To show the performance of SPDR in a highway environment, we select a highway segment from G4 in China as the simulation area based on an actual map. The vehicles are randomly distributed in the lanes, and the vehicle speed in the simulation follows a uniform independent distribution in the range of [60, 120] km/h.

1) PARAMETER SETTINGS

Vehicles are equipped with IEEE 802.11p wireless interfaces. The other parameters for wireless nodes are listed in Table 2. The beacon interval of SPDR is set to 2 seconds to update positions and speed. The EM interval is set to 0.5 seconds. As the delay of electromagnetic wave propagation in the air is negligible, we set $WT_{\max} = t_r$ to 40 ms. We also enable the store-carry-forward manner in the multi-hop forwarding when there is no next-hop neighbor available around. The carrying time for EMs is set to 18 seconds.

TABLE 2. Simulation parameter setup.

Parameter	Parameter Settings
MAC protocol	IEEE 802.11p
Transmission range	250 m
Channel capacity	2 Mbps
Interface buffer length	60 packets
EM size	256 bytes

2) PERFORMANCE METRICS

We compare our proposed SPDR with GPSR [37] and role-based multicast protocol [35] in simulations. Both of them are classic routing protocols for VANETs. GPSR adopts the distance-based greedy forwarding. Role-based multicast protocol assigns the deferral time for received vehicles based on the distance from the sender (i.e., (14)), which uses the wait-time forwarding mechanism. The following performance metrics are taken into account for our simulations.

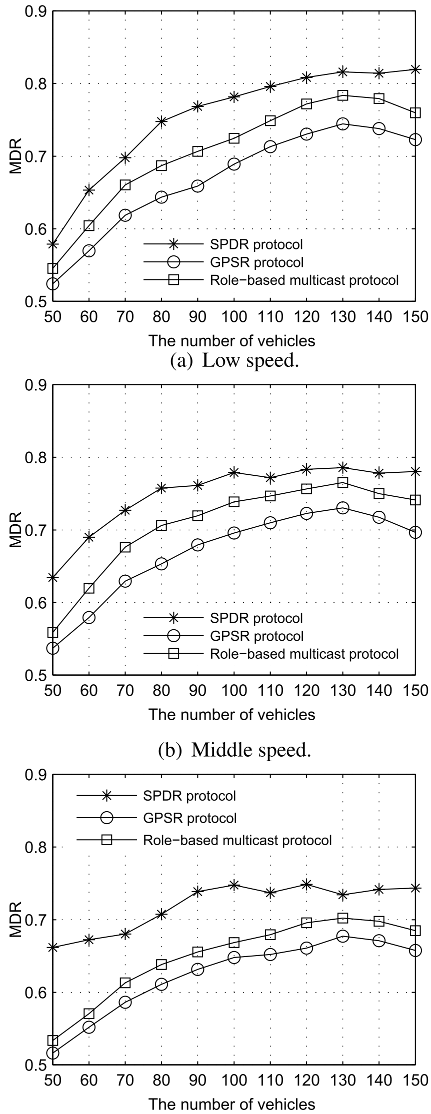
- *Message Delivery Ratio (MDR):* The successful ratio of the messages transmitted from the AV to the destination, which reflects the reliability of the routing.
- *Average Dissemination Delay (ADD):* The average end-to-end dissemination delay for successfully received messages at the destination, including the queuing delay, the transmission delay, and waiting time for rebroadcast.
- *Throughput:* The effective amount of messages successfully transmitted from the AV to the destination in a unit time in the network.

B. SIMULATION RESULTS AND PERFORMANCE EVALUATION

To study the impact of speed on routing performance, we divide the speed into low speed [60, 80] km/h, middle speed [80, 100] km/h, and high speed [100, 120] km/h. Then we evaluate our performance by varying the density of the vehicle in various speed scenarios.

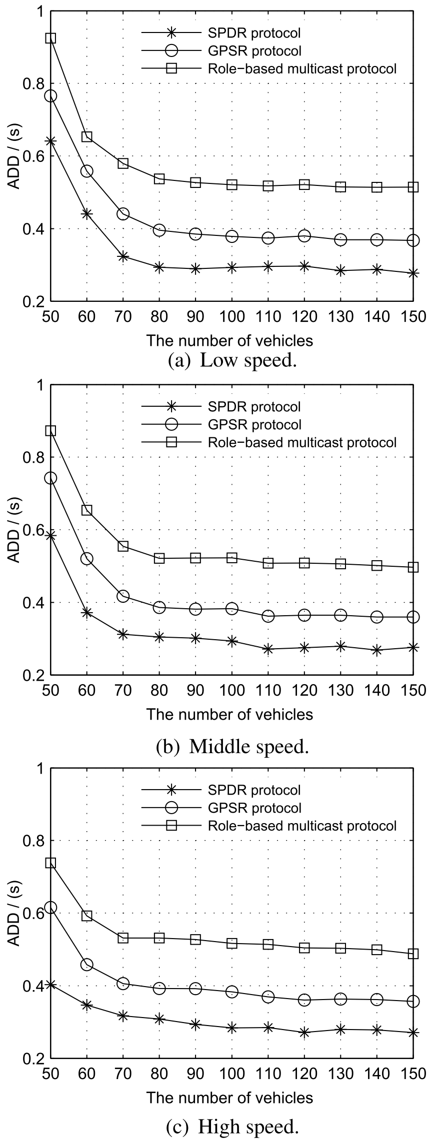
1) PERFORMANCE OF MDRs

Fig. 6 shows the successful delivery ratio from the AV to the destination with different numbers of vehicles in three-speed scenarios. The MDRs of SPDR are always higher than those of GPSR and role-based multicast protocol. When the vehicle density is low, there is no wireless multi-hop path among some vehicles. Due to the lack of relay vehicles available to forward messages, the EMs cannot be delivered to the destination, resulting in a low MDR. As the number of vehicles increases and there are sufficient relay vehicles to forward messages, the improved network connectivity gradually increases the MDRs. However, the network will introduce more messages as the number of vehicles further increases, increasing buffer overflow or the probability of packet collisions. The number of forwarding failures due to collisions increases, resulting in fewer MDRs. Our SPDR uses collaborative forwarding to cope with the forwarding failure problem so that its MDRs tend to be stable, while those of GPSR and role-based multicast protocol decrease when the number of vehicles is larger than 130.



(a) Low speed.
(b) Middle speed.
(c) High speed.

FIGURE 6. MDRs of the routing protocols with different numbers of vehicles.

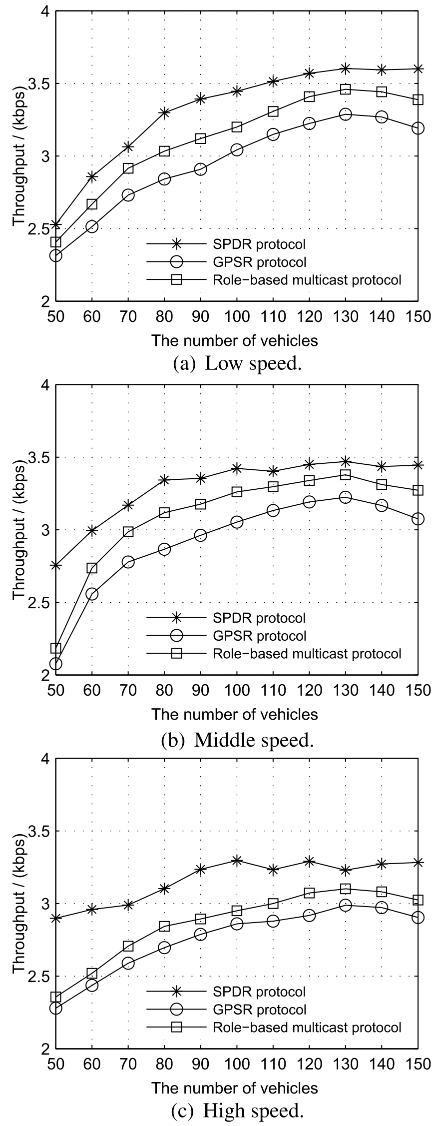


(a) Low speed.

(b) Middle speed.

(c) High speed.

FIGURE 7. **ADDs of the routing protocols with different numbers of vehicles.**



(a) Low speed.

(b) Middle speed.

(c) High speed.

FIGURE 8. **Throughput of the routing protocols with different numbers of vehicles.**

Together with the results in Fig. 6, we can also see that the role-based multicast protocol achieves a higher MDR than GPSR. This is because all receivers have the opportunity to participate in message forwarding in the role-based multicast protocol, improving the message reception rate. In addition, by comparing Fig. 6(a), 6(b), and 6(c), the MDRs of the three protocols decrease as the velocity increases. In this case, the major reason for the packet drops is that the forwarder may use outdated neighbor information to make routing decisions due to high speed, or the selected relay may leave the reception range of the sender. Our SPDR selects the next-hop in the shrunk RDA can enhance the stability of the selected relay as much as possible, which can achieve the highest MDRs.

2) PERFORMANCE OF ADDs

It is shown in Fig. 7 that the ADDs of the three protocols diminish as the number of vehicles increases in three-speed scenarios. When the number of vehicles is small, the forwarder may not have an available next-hop to forward EMs. In this case, the vehicle has to store-carry-forward messages, resulting in a higher ADD. The growing number of vehicles enhances the network connectivity, which can reduce the probability of this happening and reduce the ADDs. Since the saturated network connectivity balances the number of EMs' hops from the AV to the destination, the ADDs gradually tend to be stable when the number of vehicles is larger than 130. Since our SPDR dynamically sets the RDA range to ensure reliable timely forwarding of messages and reduce retransmissions, it achieves lower ADDs than those of GPSR and role-based multicast protocol under different vehicle densities. Moreover, SPDR and GPSR forward emergent data immediately without wait time. However, the receivers have to wait until their wait time expire per forwarding in the role-based multicast protocol. The accumulated wait time per hop increases the dissemination delay, resulting in the highest ADDs. Compared to vehicle density, speed changes hardly affect network connectivity, so the impact of speed on the ADDs is minimal.

3) PERFORMANCE OF THROUGHPUT

As shown in Fig. 8, although the throughput of the three protocols decreases as the speed increases, SPDR still achieves the highest throughput with the highest MDR and the lowest ADD as compared to GPSR and the role-based multicast protocol. As the number of vehicles increases, the throughput of the three protocols first increases, and then the throughput of SPDR tends to be stable. Accordingly, the throughput of GPSR and role-based multicast protocol decreases when the number of vehicles is larger than 130 in the simulations.

VI. CONCLUSION

To fulfill the real-time constraints of EMs, we have proposed a speed and position aware dynamic routing (SPDR) for disseminating EMs on the multi-lane motorway scenario. It is jointly designed with speed metric dynamic greedy routing and collaborative forwarding strategy. To ensure reliable forwarding, we use the speed metric greedy routing to schedule the optimal next-hop to retransmit. When forwarding suffers from failure, we deploy the collaborative forwarding strategy to enhance successful delivery. Simulation results indicate that our proposed SPDR performs superior to GPSR and role-based multicast protocol in message delivery ratio, average dissemination delay, and network throughput.

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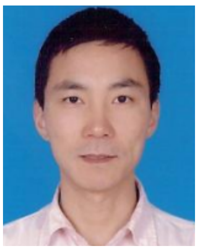
RUIYAN HAN received the B.S. degree from Harbin Normal University, Harbin, China, in 2013, and the M.S. degree from Yunnan Minzu University, Kunming, China, in 2016. She is currently pursuing the Ph.D. degree with the School of Electronic and Information Engineering, South China University of Technology, Guangzhou, China. Her current research interests include vehicular *ad hoc* networks and wireless sensor networks.



JINGLUN SHI received the B.S., M.S., and Ph.D. degrees from the School of Electronic and Information Engineering, South China University of Technology (SCUT), in 1999, 2000, and 2004, respectively. Before joining SCUT, he was a Postdoctoral Research Associate at Seoul National University. During his graduate program, he was a Research Fellow at Hong Kong Baptist University and Torento University. His research interests include wireless sensor networks, exoskeleton robot, and artificial intelligence.

QUANSHENG GUAN (Senior Member, IEEE) received the Ph.D. degree from the South China University of Technology (SCUT), in 2011.

From 2009 to 2010, he was a Visiting Ph.D. Student with The University of British Columbia, Canada. From 2012 to 2013, he was a Postdoctoral Researcher with The Chinese University of Hong Kong. He was a Visiting Scholar with the Singapore University of Technology and Design, in 2013, and a Visiting Professor at Polytech Nantes, France, in 2016. He is currently a Full Professor with the School of Electronic and Information Engineering, SCUT. His research interests include wireless networks, underwater acoustic networks, and cloud/fog computing. He is the co-recipient of Best Paper Awards from IEEE ICCC 2014 and IEEE ICNC 2016, Best Demo Award from ACM WUWNET, in 2018. He is also an Associate Editor of IEEE Access, *International Journal of Distributed Sensor Networks*, and a Guest Editor of *Mobile Information System*.

FARHAD BANOORI received the B.S. degree in electrical communication engineering from Fast University, in 2014, and the M.S. degree in telecommunication and network from Bahria University, in 2017, Pakistan. He is currently pursuing the Ph.D. degree with the South China University of Technology, Guangzhou, China.

His research interest includes 5G wireless communication systems. His research topics have widened to wireless communication systems, machine learning, energy efficiency enhancement by transmitter linearization techniques regarding PAPR reduction and high-power amplifier characterization within OFDM, MIMO-OFDM and massive MIMO technologies for both terrestrial and underwater ambient.

WEIQIANG SHEN (Member, IEEE) received the Ph.D. degree in computer application technology from Jinan University, Guangzhou, China, in 2019. He is currently a Lecturer with the School of Electronic and Information, Guangdong Polytechnic Normal University, Guangzhou. His current research interests include wireless sensor networks, vehicular networks, the Internet of Things, and computational intelligence.