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An Adaptive and Opportunistic Broadcast Protocol for Vehicular Ad Hoc Networks

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Abstract: A primary goal of broadcasting in vehicular ad hoc network (VANET) is to improve the road safety by transmitting alert messages to all surrounding vehicles as soon as possible. In this paper, we adopt the concept of opportunistic routing and propose a multiple candidate relays opportunistic broadcast (MCROB) protocol for VANET. The MCROB protocol is a sender-driven broadcast scheme independent of node density. The packet delivery ratio (PDR) is derived and an expected transmission speed (ETS) for the MCROB is proposed. A priority rule for selecting a proper candidate relay and an adaptive algorithm for forwarding timers of candidate relays are also presented in this paper. Simulations show that MCROB is adaptive to the rapid changing of network conditions. It keeps a low communication overhead introduced by the broadcast and increases the average transmission speed by around 40%.

Keywords: Broadcast storm, opportunistic broadcast, multiple candidates, transmission speed, vehicular ad hoc network (VANET).

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1 Introduction

A very promising direction in intelligent transportation system is the applications based on vehicular ad hoc network (VANET). VANET can improve the safety of the transportation system. For example, safety applications could be used to provide drivers with early warnings and avoid accidents. VANET is considered as a specific type of mobile ad hoc network (MANET). The rapidly changing topology of VANET poses many challenging research issues, especially in multi-hop broadcasting. Broadcasting in VANET requires high reliability and efficiency for delivering emergency messages in safety applications. However, the absence of packet acknowledgment, packet retransmission, and medium reservation scheme makes it difficult to achieve this goal.

Broadcasting in VANET can be either receiver-driven, which means that the next-hop is decided on the fly (as in most broadcasting protocols), or it can be sender-driven, which means that the next-hop node is determined before the transmission. Receiver-driven broadcasting makes full use of the broadcast nature of wireless propagation, and all the nodes that receive the packet correctly have the chance to forward the packet. To solve the broadcast storm problem[1], the nodes which receive the packet collaborate with the other and then decide which nodes should forward the packet. However, this kind of scheme does not consider the node density and could not properly deal with all kinds of scenarios. Receiver-driven, however, has to assume that the communication range of the node is fixed and this might be unrealistic[2−4]. In the sender-driven case, the sender designates multiple candidate relays at each hop which not only takes advantage of the broadcast nature of wireless propagation but also reduces the redundant forwarding. The sender-driven protocol can promptly adjust the candidate relay set to adapt the rapidly changing network condition which is the main feature of VANET. Therefore, the sender-driven protocols are suitable for VANET.

Though the sender-driven protocols exploit the broadcast nature of wireless propagation and reduce the redundant forwarding, the existing schemes[5, 6] do not take the transmission speed into account to choose the candidate relays. Additionally, the absence of packet retransmission makes them unreliable. Therefore, the objective of this paper is to propose a sender-driven scheme which improves the transmission speed by selecting the candidate relays adaptively and enhances the reliability through retransmission.

To enhance the performance of transmission, opportunistic routing (OR)[7] exploits the random packet receptions of the neighboring nodes to improve the performance. Despite the fact that OR was designed for unicast, we can utilize the same idea to design a broadcast protocol for VANET because of its linear topology (i.e., it has only one or two transmission directions on the road). Introducing the idea of OR into the design of VANET broadcasting faces the following challenges:

1) OR requires the global topology and link state to select proper candidates while it is hard to collect such information for VANET because of rapid movement of the nodes.

2) Traditional OR mainly decreases the number of transmissions to enhance the performance of end-to-end throughput, but the delivery latency, rather than number of transmissions, is the dominant performance criterion for VANET broadcasting especially in emergency messages transmission.

As a result, the candidate selection algorithms of OR cannot apply to VANET broadcasting directly.

The main contributions of this paper are as follows:

1) We propose an multiple candidate relays opportunistic broadcast protocol (MCROB) for highway VANET. The objective of this work is to maximize the transmission speed to improve the throughput. It designates the candidate relays and assigns their priorities before broadcasting a packet to avoid the collisions of receivers. It can reduce the redundant transmission and keep the communication overhead at a low-level regardless of network node density. It also adds the retransmission strategy to enhance the reliability.

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2) We develop a new broadcasting metric (i.e., expected transmission speed (ETS)) for the candidate relay selection.

3) We propose an adaptive algorithm to estimate the coordination delay and it reduces the delivery latency significantly.

The remainder of this paper is organized as follows. Section 2 introduces the related works in the field of broadcasting in VANETs. Our proposed scheme is presented in Section 3. Then, we evaluate the performance of our proposed scheme in Section 4. The last section concludes the paper.

2 Related works

In recent years, researchers have realized the importance of exploiting an efficient and reliable broadcast protocol for VANET. Many broadcast protocols have been proposed to deal with broadcast storm problem.

To avoid collision, urban multihop broadcast (UMB) proposed in [8] broadcasts request to broadcast/clear to broadcast (RTB/CTB) handshake before sending the data packets. Similar to UMB, position based multi-hop broadcast protocol (PMBP)[9] broadcasts a broadcast request to send (BRTS) packet at each hop before sending the data packets in order to select the farthest neighboring node as the next hop forwarder. To avoid the redundant broadcasting from other nodes, opportunistic broadcast[10] sets a broadcast backoff timer in media access control (MAC) layer and calculates the backoff delay according to the distance and the local vehicle density. The work in [11] proposes weighted-persistence (Weighted-p), slotted 1-persistence (Slotted-1) and slotted p-persistence schemes (Slotted-p). The Weighted-p scheme sets a forward probability to be inversely proportional to the distance from the sender. In this method, however, the probabilistic forwarding leads to redundant rebroadcasts. The other broadcast technique, Slotted-1, uses a preassigned time slot to decide when to rebroadcast the message. How to choose a precise number of slots is a difficult task in Slotted-1 scheme because of the variety of traffic load. Another problem is that the total end-to-end delay is significantly longer than that in the flooding case in sparse network scenario. Similar to Slotted-1, Slotted-p rebroadcasts with the predetermined probability p at the assigned time slot. Vehicle-density-based emergency broadcast (VDEB)[12] scheme partitions the transmission range of the current forwarder into multiple concentric rings. As the ring width is determined according to the estimation of the node density, it will be inserted into the broadcast message to notify the receivers. The receiver can then compute the waiting time according to the received ring width.

All of the above protocols are receiver-driven, while the followings are sender-driven. Multipoint relaying (MPR)[5] restricts the number of forwarders to a small set of neighbour nodes instead of all neighbors and proposes a heuristic method for the selection of multi-point relays. The difficulty of MPR is keeping the relay set as small as possible to reduce the number of redundant transmissions. Enhanced selective forwarding (ESF)[6] designates multiple candidate forwarders which have the same moving direction as the sender with different priorities. In a dense network, however, multiple spatially-close nodes may have a high chance to be interfered by hidden nodes. The absence of packet retransmission decreases the probability of message′s reception[4].

Most of the existing opportunistic routings use global topology and link quality information to select and prioritize the forwarding candidates[7, 13, 14]. In order to acquire these information, periodic network-wide measurement is required, which does not work in highly dynamic VANET. Reference [15] proposes position based opportunistic routing protocol (POR) which takes advantage of the stateless property of geographic routing and the broadcast nature of wireless medium. The packet is transmitted to the next hop forwarder as unicast in IP layer and multiple candidates receive the packet using MAC interception. The priority of the forwarding candidate is decided by its distance to the destination. The closer it is to the destination, the higher priority it will get.

The aforementioned schemes have an advantage in that they can partially mitigate the broadcast storm problem and MAC layer collisions[16, 17]. However, they cannot be adaptive to the rapidly changing topology of VANET and do not take the transmission speed into account. Our studies focus on network layer and aims to solve the broadcast storm problem and improve the transmission speed under highly dynamic VANET. To cope with the dynamic topology, the proposed scheme estimates the value of the forwarding timer using an adaptive algorithm and speeds up the transmission.

3 Protocol design

3.1 Overview

Some broadcast schemes[6,8−12,18], try to greedily select the farthest neighboring node to forward the packet, but the problem is that under unreliable wireless channel the farther the distance, the greater the probability of packet loss, especially in networks with higher node densities[19].

Based on the idea of opportunistic routing and the phenomenon discussed above, we propose a multiple candidate relays opportunistic broadcast scheme, i.e., MCROB. Similar to MPR and ESF, MCROB designates multiple candidate forwarders with different priorities in the packet header and broadcasts the packet. Upon hearing the transmission, the nodes which are not on the candidate list simply discard the packet. Nodes which are on the candidate list store the packet and set forwarding timers based on their priorities. Upon timer expiration, the node forwards the packet and all other candidates overhearing this transmission simply remove the corresponding packet from their queues to avoid duplicate transmissions. When all the candidates fail to forward, the sender will retransmit the packet. Each candidate that rebroadcasts successfully also chooses multiple candidate relays and repeats this process.

MCROB only needs the local topology knowledge (i.e., one-hop neighbors) to choose the proper candidates. Considering the transmission speed, MCROB uses a new local metric ETS discussed in Section 3.2 to choose the candidate relays and assign the priorities for them. To adapt the various scenarios, MCROB uses an instantaneous estimation algorithm to set an adaptive waiting timer. This process will be described in detail in Section 3.5.

3.2 Transmission speed of opportunistic broadcast

We define the one-hop forwarding time (OFT) as the period from the time when the sender/forwarder is going to transmit the packet to the time when the receiver receives the packet. As given by (1), OFT can be divided into three parts: channel access delay (T_c), data transmission time (T_d), and propagation delay (T_p).

$$\mathrm{OFT} = T_c + T_d + T_p. \tag{1}$$

For a CSMA/CA protocol, T_c is the time needed by the sender to acquire the channel before it transmits the data packet, which includes the back-off time and coordination function distributed interframe space (DIFS). T_d can be further divided into two parts: protocol header (the length varies in our protocol) transmission time and data payload transmission time. T_p is the time taken by the signal to propagate from the sender to the receivers, which can be ignored here.

Since broadcast does not have acknowledgement mechanism, before broadcasting the packet, lower priority candidates always need to wait for a certain period of time to confirm that higher priority candidates have not relayed the packet. This period is at least one OFT.

As shown in Fig. 1, we define the ordered set (i.e., candidate relay set, CRS) of the candidate relays i for the packet sent by sender S as:

$$\mathrm{CRS}_S = \{n+1, n, n-1, n-2, \cdots, 1\}. \tag{2}$$

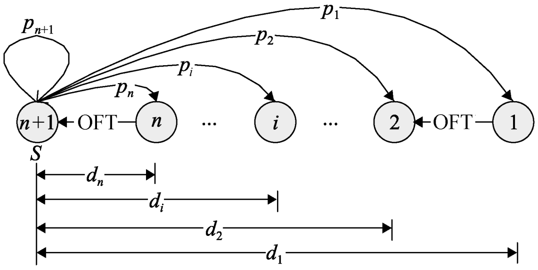


Fig. 1 An example of multiple candidates

For simplicity, we assign higher priority to node that is located farther away from the sender (prioritization will be discussed in Section 3.3). Node 1 has the highest priority and node S, as the candidate $n+1$, has the lowest priority. We define the probability that candidate i receives a packet from the sender S as p_i and d_i denotes the distance between sender S and candidate i, specifically, $p_{n+1} = 1$, $d_{n+1} = 0$.

We assume S finishes sending of the packet at time 0 and node 1 receives the packet successfully and forwards it taking no time. Therefore, the transmission time of this hop is one OFT and the other candidates would cancel their pending transmissions at time 1×OFT. If node 2 receives the packet correctly and has not received any duplicate packets within one OFT, it knows that node 1 fails to receive the packet and broadcasts it at time 1×OFT. The total transmission time is two OFT and then the other candidates would give up the retransmission at 2×OFT and so on.

According to the above analysis, for a given candidate relay set CRS, we now propose a new local metric, expected transmission speed (ETS), as

$$\mathrm{ETS} = \mathrm{ETD}/\mathrm{ETT} \tag{3}$$

where ETD is the expected transmission distance and ETT is the expected transmission time. ETT can be computed as

$$\mathrm{ETT} = \sum_{i=1}^{n+1} \mathrm{E}[\mathrm{OFT}] \cdot i \cdot p_i \prod_{k=1}^{i-1} (1 - p_k) \tag{4}$$

where E[OFT] is the expected one-hop forwarding time. Obviously, ETD can be expressed as

$$\mathrm{ETD} = \sum_{i=1}^{n} d_i p_i \prod_{k=1}^{i-1} (1 - p_k). \tag{5}$$

3.3 Candidate relay set selection and priority scheduling

The existing studies[7, 13, 14] of opportunistic routing mainly focus on the network throughput and the number of transmissions. ExOR[7] uses the ETX (expected transmission count), which captures the minimum number of total transmissions to send a packet from a certain node to the destination, as routing metric to select candidate forwarders along the best path. These protocols are designed for static mesh networks. Thus, the candidate selection algorithm of opportunistic routing cannot be directly applied to VANET broadcasting. Unlike the previous metric, we use ETS to consider the performance of broadcast transmission speed, and evaluate the impact of the candidate selection on the ETS.

Consider a simple example shown in Fig. 2, the packet delivery ratio (PDR) and distances are labeled on the curves. For simplicity, every transmission selects only one candidate and the node keeps transmitting the same packet until the candidate receives it. The expected number of transmissions ENT for distance d can be computed as

$$\mathrm{ENT} = \frac{1}{\mathrm{PDR}} \cdot \frac{d}{d'} \tag{6}$$

where d' is one-hop distance. There are two options for candidate selection: one is to choose the farther node as the candidate, i.e., the path is $\{S, C2, D\}$; the other is to choose the nearer node as the candidate, i.e., the path is $\{S, C1, C2, C3, D\}$. Using (6), the expected number of transmissions from S to D using the former option is $(1/0.4) \times (400/200) = 5$ and for the latter case is $(1/0.8) \times (400/100) = 5$. Both of them need 5 transmissions to deliver a packet to the destination because of the same ETD in one hop, i.e., $200 \times 0.4 = 100 \times 0.8 = 80$. Consider the coordination among candidates, lower priority candidate must wait one OFT before it can forward/retransmit the packet. We use the function ETS(CRS) to denote the ETS for the ordered candidate relay set CRS. We can see that the ETS for the former case discussed above is $\mathrm{ETS}(\{C2\}) = 50/\mathrm{E}[\mathrm{OFT}]$ and for the latter case it is $\mathrm{ETS}(\{C1\}) = 66.7/\mathrm{E}[\mathrm{OFT}]$. The result of this example shows that even though different approaches have the same total number of transmissions, they may have different ETS.

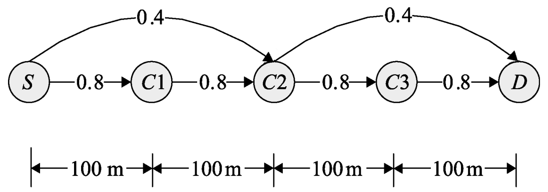


Fig. 2 The impact of the candidate selection on the ETS

Consider the case that selects multiple candidates in Fig. 2, though ETS($\{C1\}$) = 66.7/E[OFT] is larger than ETS($\{C2\}$) = 50/E[OFT] in the case that only one candidate is chosen, ETS($\{C1, C2\}$) = 72.73/E[OFT] is smaller than ETS($\{C2, C1\}$) = 74.42/E[OFT] while choosing two candidates. This result shows that the faster candidate, who is chosen in the one candidate limited case, does not necessarily get the higher priority in multiple candidate case.

In the following, we propose the candidate relay set selection and prioritization rule. Let R be the set of the sender′s neighbors and $n = |R|$, which is the number of nodes in R. A straightforward way to find the optimal ordered candidate relay set to maximize the ETS is to try all the ordered subsets of R, which run in factorial time-complexity (i.e., O(n!)). It is, however, not feasible when n is large. Even though the size of CRS is limited to a constant, such as 5, the complexity is still not acceptable. The fundamental reason for the high complexity of the optimal solution is that there is no total order among nodes so that a node′s candidates can be uniquely determined by a single metric, such as the ETX of ExOR[7].

Instead of the exhaustive search, we introduce a priority rule to get a solution approaching the optimal ETS. This priority rule allows us to notably reduce the complexity of the candidate selection and prioritization.

Priority rule: Let $C1$ and $C2$ be any two neighbors of the sender. If ETS($\{C1, C2\}$) > ETS($\{C2, C1\}$), the priority of $C1$ is higher than $C2$, otherwise, the priority of $C2$ is higher than $C1$.

Using this priority rule and a quick sort algorithm, the time-complexity is reduced from O(n!) to O($n$log$n$). When a sender finishes the sorting procedure, it chooses the neighbour with the highest priority as a candidate and removes it from the neighbour set. The sender repeats this procedure to choose all candidates until it reaches the candidate set size limit.

3.4 Packet delivery ratio estimation

In realistic vehicular environments, packet delivery ratio (PDR) (i.e., the probability that a message is received by a node at a specific distance) is affected by various factors — including fading effect, doppler effect, hidden node, the distribution of the nodes, and so on. Most of the protocols measure the received signal strength indicator (RSSI) or send a probe packet periodically to estimate the link quality[7]. However, [20] shows that RSSI has little use to predict communication reliability. Therefore, it is hard to use the RSSI to estimate the PDR in VANET. Reference [20] also shows that the temporal correlation is weak in the vehicular environments (i.e., bursty effects are common). It indicates that long term measurement, such as probe packet, has little practical significance.

MCROB does not require a very accurate measurement of link quality. Therefore, we roughly use the radio propagation model to estimate the PDR at a specific distance from the sender (in the absence of other node′s interferences). Several studies[2−4] have shown that the realistic non-deterministic Nakagami-m fading model is a suitable channel model for simulation of highway scenarios. Therefore, we select the Nakagami-m fading model to estimate the PDR. The Nakagami-m fading probability density function that describes the distribution of the power x of a received signal can be expressed as

$$f(x;m,\Omega)=\frac{2m^m}{\Gamma(m)\Omega^m}x^{2m-1}\mathrm{e}^{-\frac{m}{\Omega}x^2},\quad x\geqslant 0,\Omega\geqslant 0,m\geqslant\frac{1}{2} \tag{7}$$

where Γ is the Gamma function, m is the shape parameter, and Ω is the average received power. According to [4], we take the average value m as 3 for distance smaller than 50 m, decrease it to 1.5 for distance between 50 m and 150 m, and make it 1 for distance higher than 150 m.

Assuming two-ray ground signal propagation, Ω can be expressed as (8) as a function of d, the distance between the sender and receiver.

$$\Omega(d)=P_t\frac{G_tG_rH_t^2H_r^2}{d^nL} \tag{8}$$

where P_t is the transmit power, G_t and G_r are antenna gains of transmitter and receiver, respectively, H_t and H_r are antenna heights of transmitter and receiver, respectively, L is the system loss and n is the path-loss exponent. We set $G_t = G_r = 1$, $H_t = H_r = 1.5\,\mathrm{m}$, $L = 1$ and $n = 4$ in our simulation.

We assume a packet is received successfully if the received signal power is stronger than the receiving power threshold. Then, by using (7) and (8), we can derive the PDR at a certain distance d (for completeness, the derivations are given in the appendix).

3.5 Instant retransmission time estimation

Most of the protocols set a predetermined waiting timer for the receiving nodes to rebroadcast the packet, such as the *WAIT_TIME* of Weighted-p and Slotted-1, the *SlotTime* of VDEB and the *msg_holding_time* of ESF. To speed up the transmission, MCROB sets an adaptive waiting timer called coordinative retransmission timer (CRT) for the receiving candidates and the sender. The sender adds the value of OFT into the packet header and broadcasts the packet. Then, the CRT should be set as follows

$$\mathrm{CRT}=(i-1)\times\mathrm{OFT} \tag{9}$$

where i is the priority of the candidate.

If the CRT of the low priority candidate expires before the high priority candidate sending the packet, it leads to redundant rebroadcasts and decreases the gain of the opportunistic broadcast. In order to make full use of the opportunistic gain, it is necessary to set OFT sufficiently large to inhibit low priority candidate from rebroadcasting. However, OFT cannot be indefinitely large since it may cause a long coordination delay and subsequently, slows down the

ETS. Hence, there is a tradeoff relation between the opportunistic gain and the ETS.

Algorithm 1. Computing the OFT and CRT

```
1. Initialization:
2. $Last\_Measure\_Time \leftarrow 0, First\_Measure \leftarrow$ true
3. Receiving:
4. if non-retransmission then
5.   Calculate the $m$OFT using (10)
6.   if $Current\_Time - Last\_Measure\_Time > \delta$ then
7.       $First\_Measure \leftarrow$ true
8.   end if
9.   if $First\_Measure$ then
10.      SOFT← $m$OFT
11.      OFTVAR← $m$OFT/8
12.      OFT← $m$OFT ×1.25
13.      $First\_Measure$ ←false
14.    else
15.      OFTVAR← OFTVAR + $beta$×(abs($m$OFT −
         SOFT) − OFTVAR)
16.      SOFT← SOFT + $alpha$ × ($m$OFT − SOFT)
17.      OFT← SOFT + 1/4×OFTVAR
18.    end if
19.    $Last\_Measure\_Time \leftarrow Current\_Time$
20. end if
21. Sending:
22. if non-retransmission then
23.    if $Current\_Time - Last\_Measure\_Time > \delta$ then
24.      $First\_Measure \leftarrow$ true
25. OFT← $Default$OFT
26.    else
27.      OFT← OFT
28.    end if
29. else
30.    OFT← OFT× 1.25
31. end if
32. if OFT > MaxOFT then
33.    OFT ← MaxOFT
34. end if
```

A more accurate OFT may improve the performance of the protocol. To design a practical adaptive algorithm to estimate the value of OFT, we have to measure the network state with the rapidly changing condition. Assuming the receiving time of the new packet is t_1, the candidate with priority i can calculate the measured OFT (mOFT) according to (10) if it receives the duplicate packet which is sent by the candidate with priority j ($j < i$) at t_2.

$$m\text{OFT} = t_2 - t_1 - (\text{OFT} \times (j-1)). \qquad (10)$$

We modify the algorithm for round trip time (RTT)[21] to compute the OFT, as show in Algorithm 1. When the node receives the duplicate packet, it calculates the mOFT if the packet has not been transmitted more than one time (i.e., non-retransmission) (line 4–5). And then if the interval of measurement is larger than the threshold δ, the algorithm will initialize the measurement again (line 6–7) to keep the measurement up-to-date. In line 9–18, the node estimates its OFT in a similar way as done in TCP. To smooth the measurement of the RTT, [21] used $alpha = 1/8$ and $beta = 1/4$ to compute the variables. However, RTT indicates the multi-hop network state while the design objective of OFT, on the contrary, reflects the rapid changing local network condition. We reverse the value of the parameters to set $alpha = 7/8$ and $beta = 3/4$ to capture this rapid changing. OFTVAR is a scaled version of mean deviation as the RTTVAR in [21], we decrease its weight from 4 to 1/4 for the purpose of fast transmitting speed (line 17). The OFT shall take an initial value of 1 ms (i.e., the default value). In the sending stage, if the sending of the packet is non-retransmission, the sender takes the latest OFT or the default value (if the measurement interval is larger than the threshold δ) to broadcast the packet (line 22–28). A retransmission will cause OFT to increase 1.25 times until it reaches the value of MaxOFT which we set to 4 ms (line 29–34). Instead of the exponential increase as in [21], we use 1.25 times to reduce the retransmission time, while quickly adapting to the current network condition.

TCP measures the RTT utilizing the acknowledgement packets which are sent by the multi-hop destination generally. However, it is enough for algorithm 1 to just measure the OFT within one-hop distance according to the definition of OFT and (9). Algorithm 1 measures the OFT utilizing the forward packets only sent by the next-hop neighbour. It means that Algorithm 1 does not introduce any communication overhead and measures the OFT promptly. Additionally, the time-complexity of Algorithm 1 is O(1). It is a simple and practical algorithm for the safe application in VANET.

4 Simulation model and results

4.1 Highway scenario and simulation parameters

To evaluate the performance of the protocols correctly, a realistic mobility model should be used in the simulations. Intelligent driver model (IDM) is one of the microscopic models that adapt a following car′s mobility according to a set of rules to maintain a safe distance and avoid collision with the lead vehicles. IDM is suitable for highway scenario and has been implemented in [22].

Based on the model implemented in [22], we create two types of vehicles: sedan (desired velocity is 35 m/s) and truck (desired velocity is 25 m/s) on a bidirectional 2.5 km highway with two lanes in each direction. As shown in Fig. 3, some vehicles are deployed on the road first according different densities. At the same time, some vehicles located in the western half of the highway are randomly chosen as the source nodes. New arrivals enter the highway from both sides and the inter-arrival time of them follow an exponential distribution[23].

Each source node generates one packet with the size 100 bytes every 100 ms and broadcasts the messages from West to East. To check the performance of these protocols with different node densities and network traffics, we use three types of network traffic to run the simulation under varied densities. In light network traffic, 5% of the vehicles generate the messages for broadcasting and 10% in medium network traffic and 20% in heavy network traffic.

Using the Network Simulator 3 (NS-3)[24] and the scenario discussed above, we evaluate the effect of Flooding, Weighted-p, Slotted-1, VDEB and ESF compared to our proposed scheme. We select 500 m as intended communication range for Weighted-p, Slotted-1, VDEB and ESF. For the sender-driven protocols, the number of candidates is set to 5 for comparability with each other. According to the communication standard for VANET, i.e., 802.11p, Table 1 lists the relevant parameters used in simulations.

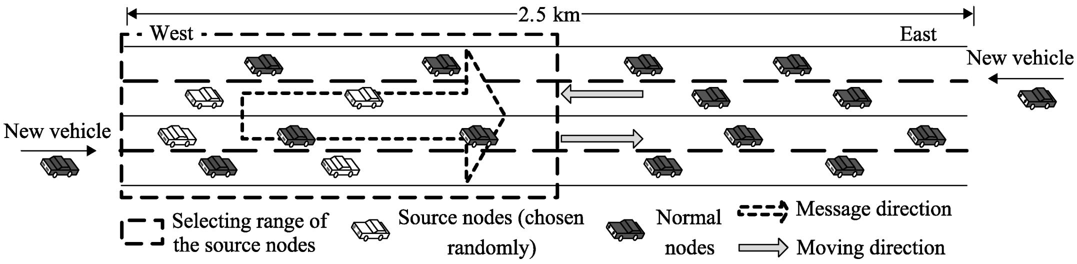


Fig. 3 Highway scenario for simulations

Table 1 Simulation parameters

Parameters	Values
SlotTime	16 μs
SIFS	32 μs
Frequency	5.9 GHz
Data rate	6 M/bps
TxPower	10 dBm
Communication range	500 m
EnergyDetectionTh	–90 dBm
CcaMode1Th	–96 dBm
TxGain	1.0 dB
RxGain	1.0 dB
Antenna height	1.5 m
Propagation model	Two-ray ground+Nakagami

4.2 Simulation results

We present the following metrics for comparing the performance of these protocols:

Reachability (RE): The number of nodes receiving the broadcast message divided by the total number of nodes that are reachable, directly or indirectly, from the source node.

Saved rebroadcast (SRB): $(r - t)/r$, where r is the number of nodes receiving the broadcast message, and t is the number of nodes which transmitted the message.

Transmission speed (TS): The average distance which the message can reach in one millisecond. We use dissemination speed instead of traditional end-to-end delay just because of the different end-to-end distance in our simulation.

Fig. 4 shows the RE with different densities and network traffics. The RE of MCROB is almost achieved to be 100% in most of the scenarios. The worst performance of MCROB is still over 94%. However, the RE of another sender-driven protocol ESF decreases with the increment of node density. The packet loss that is introduced by unreliable channel and the absence of retransmission contributes to the deterioration of the performance.

The RE of all protocols increases to 90% under the moderate density (i.e., 6–12 vehicles/km/lane). In sparse network scenario (i.e., density smaller than 6), Flooding, Weighted-p and VDEB have low RE because the broadcast process would be disrupted by the collisions of nodes with high probability. In dense network scenario (i.e., density is larger than 15), all protocols have good performance except Flooding and ESF when the network traffic is light (see Fig. 4 (a)) and only MCROB, Slotted-1 and VDEB keep the level of good performance in the moderate network traffic (see Fig. 4 (b)). With the same density, the performance of all protocols except our proposed scheme declines when they suffer from heavy network traffic which can be seen from Fig. 4 (c). The reason is that many nodes having the chance to rebroadcast the massages in dense network leads to a high probability of collision in those receiver contention-based protocols (i.e., Weighted-p, Slotted-1 and VDEB).

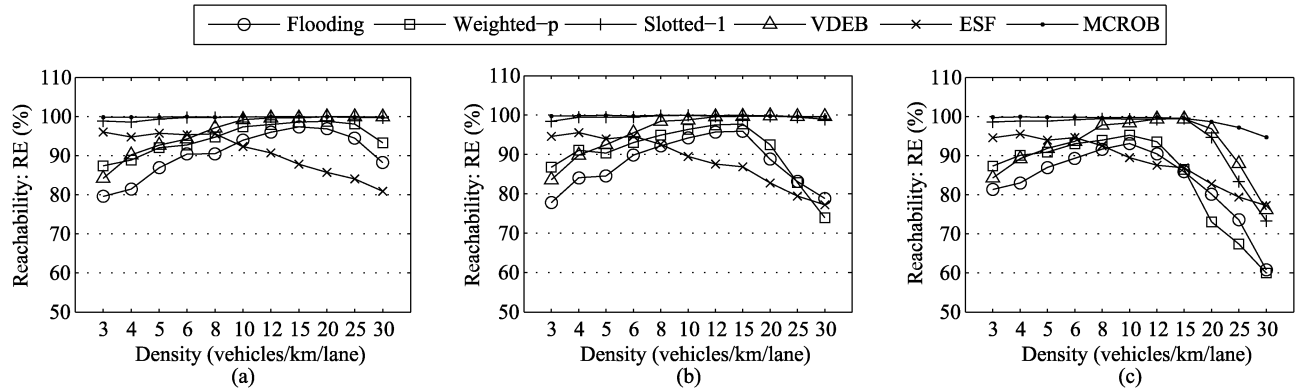
The SRB of Flooding always equals zero in the ideal channel condition. However, as shown in Fig. 5, the SRB of Flooding is not always zero because some nodes cannot receive the message to rebroadcast it, especially in high node density and high network traffic. Though forwarding with probability p, Weighted-p still introduces many redundant forwards which leads to low SRB for any cases. In the case of Slotted-1 and VDEB, the SRBs are generally higher than that of the Weighted-p case. The reason is that the nodes which have chance to forward packets are limited at foremost slots. But the SRB of VDEB is lower than Slotted-1 in case of low density, which demonstrates that the optimal slot number relies on the node density seriously.

Generally, the number of forward nodes would increase with node density. As a result, communication overhead will be heavier and consequently, TS would deteriorate quickly. In the sender-driven protocols (i.e., MCROB and ESF), however, as node density rises, SRB also goes up for all network traffics. Thus, MCROB and ESF prevent the increase of the number of forward nodes (i.e., the number is constant). It can be seen from Fig. 5 (a), (b) and (c) that the shape and the position of MCROB curves are nearly the same. Because of constant number of forward nodes, the number of the packets that are injected into the network by MCROB remains constant regardless of the node density. This advantage of MCROB becomes more prominent as the node density and network traffic increase. Inversely, the SRBs of Slotted-1 and VDEB drop gradually in the case of high density and high network traffic (see Fig. 5 (c) for density 20–30) because more collisions would happen.

Finally, we study the transmission speed that can be observed from Fig. 6. Because a candidate relay node experiences the same delay irrespective of its distance from the sender, MCROB overcomes the problem of a long waiting time in a sparse network and also keeps the good performance. It can also be observed that a clear performance deterioration exists for these protocols when the density and network traffic increase except for MCROB and ESF. The reason is that collisions occur more easily. For example, more nodes are assigned to a common time slot in Slotted-1 and VDEB, or more nodes are assigned to a high probability of forwarding in Weighted-p, or more nodes rebroadcast the packet with probability 1 in Flooding.

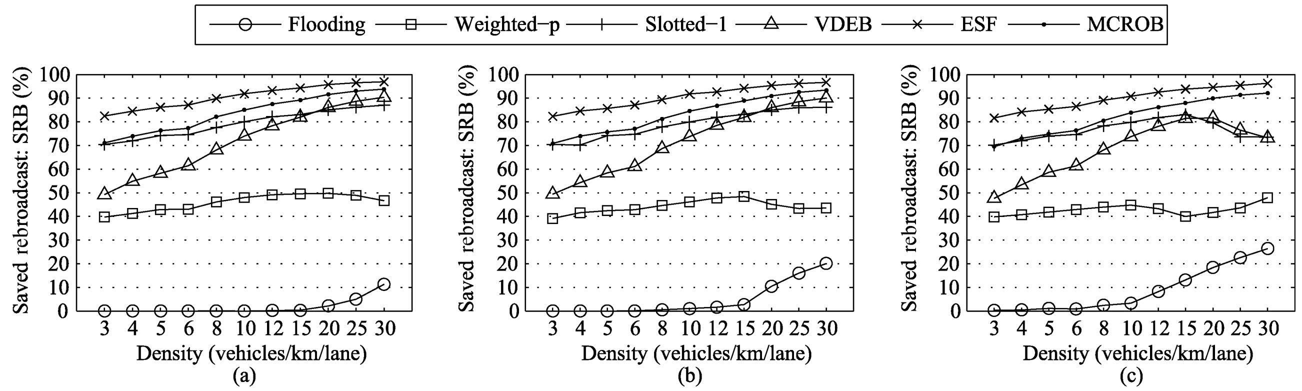
In high node density conditions, MCROB and ESF diminish the number of redundant packets by assigning fixed number candidate relays. This approach can reduce the load of the link effectively. For this reason, the transmission speeds of MCROB and ESF are still larger than 100 m/ms. Moreover, the TS of MCROB is still larger than 250 m/ms except high density and high traffic scenarios while the TS of ESF remains steady at about 180 m/ms. One advantage of MCROB is the OFT estimation and the adaptive CRT compared to ESF. Fig. 7 shows the mOFT and the OFT with different densities and traffics. Larger OFT would bring long delay and smaller OFT would introduce redundancy. So the OFT should be set adaptively according to different situation. It can be seen from Fig. 7 that Algorithm 1 estimates a suitable OFT which is about 1.6 times the value of mOFT in all cases.

To analyze the adaptivity of OFT, we use different sizes of broadcast packets to show different values of OFT. Fig. 8 shows the case that the packet size equals 300 bytes. OFT is about 1.5 times the value of mOFT in any scenario and rises slowly with node density. It is similar to the case of 100 bytes. The OFT that Algorithm 1 estimates can promptly reflect the changing of real OFT. Taking the advantage of OFT estimation, MCROB keeps high TS in all the cases.



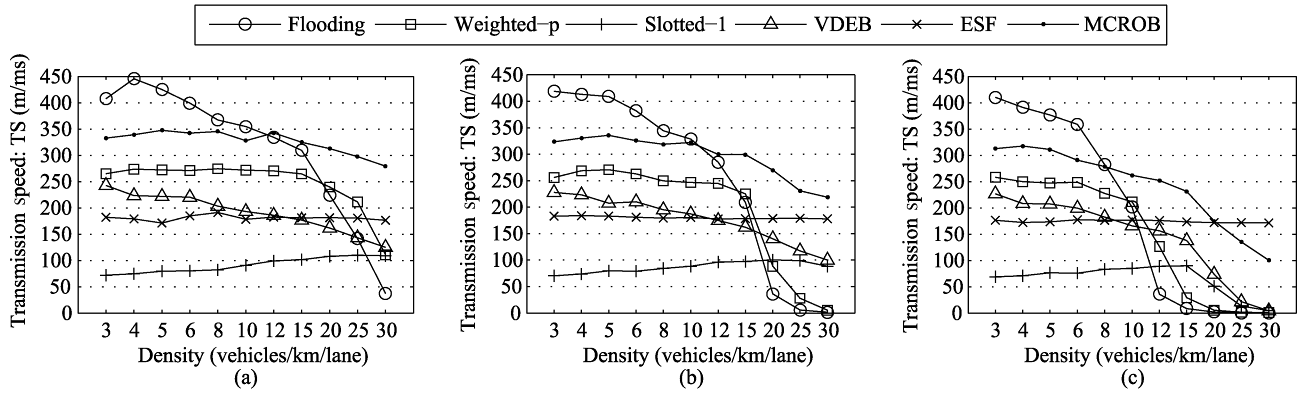
(a) (b) (c)

Fig. 4 Reachabilities at different network traffics: (a) Light load; (b) Medium load; (c) Heavy load



(a) (b) (c)

Fig. 5 Saved rebroadcast at different network traffics: (a) Light load; (b) Medium load; (c) Heavy load



(a) (b) (c)

Fig. 6 Transmission speeds at different network traffics: (a) Light load; (b) Medium load; (c) Heavy load

The TS of ESF is higher than that of MCROB under high density and high traffic (i.e., the density is 30 vehicles/km/lane and the traffic is 20%), but its RE is very low, i.e., 77.24%, as shown in Fig. 4. It means that the broadcast process has been disrupted. ESF sends a packet that reaches a short distance in a short time, consequently it keeps high TS. In contrast, the TS of MCROB is still up to 100.54 m/ms while the RE, as can be seen from Fig. 4, also keeps the level of good performance (i.e., 94.7%). The average TS of MCROB is 242.5 m/s. It increases by 40% compared to ESF′s average TS.

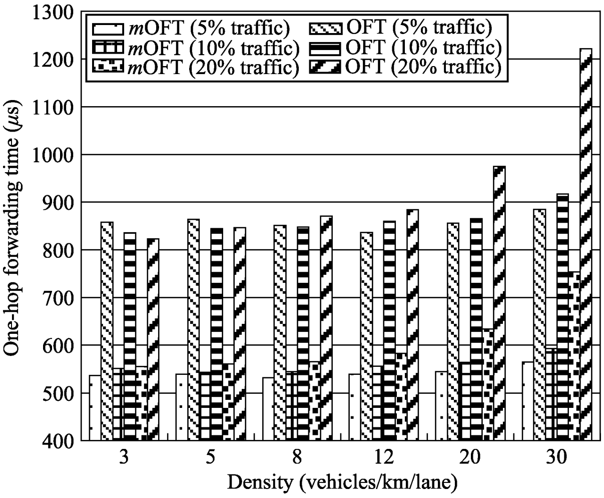


Fig. 7 One-hop forwarding time for packet size of 100 bytes

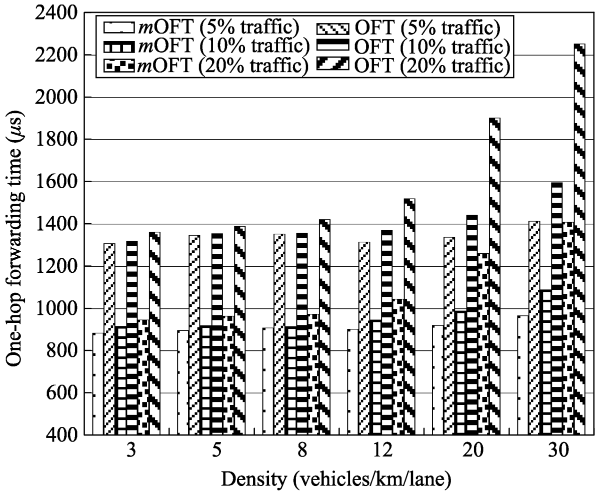


Fig. 8 One-hop forwarding time for packet size of 300 bytes

5 Conclusions

In this paper, we present an efficient multi-hop MCROB protocol for highway VANET. MCROB is a sender-driven broadcast protocol which adopts the concept of opportunistic routing. Unlike previous studies which focus on maximizing throughput or minimizing the number of transmissions, we take the factor of transmission speed into account and propose a broadcast metric ETS to select the proper candidates.

We compare the performance of MCROB with existing broadcast schemes by using NS-3. Simulations show that the MCROB protocol outperforms existing solutions in terms of RE, SRB and TS. We can conclude from the results that the main advantages of MCROB are as follows: 1) It does not require global network topology and link information which are hard to measure in VANET. 2) It introduces the retransmission strategy to enhance the reliability of broadcast. 3) Since the number of candidates is fixed and their priorities are predetermined, candidates are collision free and only one candidate has to rebroadcast the packet finally. As a result, MCROB introduces the same load into the network regardless of the node density. 4) It sets the parameters irrespective of the node density and estimates the one-hop forwarding time dynamically. MCROB maintains a consistent performance level in all node densities.

In the future works, the optimal selection of candidates can be further improved by considering more characteristics of VANET and the network traffic. Besides, the number of candidate relays can also be optimized. Moreover, future work involves developing a new broadcast protocol which supports the city scenario.

Appendix

Derivation of the packet delivery ratio

The probability density function (pdf) of the Nakagami-m distribution is

$$f(x;m,\Omega)=\frac{2m^m}{\Gamma(m)\Omega^m}x^{2m-1}\mathrm{e}^{-\frac{m}{\Omega}x^2},\quad x\geqslant 0,\Omega\geqslant 0,m\geqslant\frac{1}{2}. \tag{A1}$$

Assuming the signal amplitude follows the Nakagami distribution, the power of the signal follows the gamma distribution, given by

$$p(x;m,\Omega)=\frac{m^m}{\Gamma(m)\Omega^m}x^{m-1}\mathrm{e}^{-\frac{m}{\Omega}x}. \tag{A2}$$

Its cumulative distribution function is the regularized gamma function:

$$F(x;m,\Omega)=\int_0^x f(u;m,\Omega)\mathrm{d}u=P(m,\frac{m}{\Omega}x) \tag{A3}$$

where P is the incomplete gamma function (regularized). It can be expressed as

$$P(m,\frac{m}{\Omega}x)=\frac{1}{\Gamma(m)}\gamma(m,\frac{m}{\Omega}x) \tag{A4}$$

where γ is the lower incomplete gamma function. We assume a packet is received successfully if the received signal power is greater than the receiving power threshold RxTh. The received signal power x is greater than RxTh with the probability:

$$\begin{aligned}P(m,\frac{m}{\Omega}x|x>\mathrm{RxTh})=1-\frac{1}{\Gamma(m)}\gamma(m,\frac{m}{\Omega}\mathrm{RxTh})=\\ 1-\frac{1}{\Gamma(m)}\gamma(m,t)\end{aligned} \tag{A5}$$

where $t=\frac{m}{\Omega}\mathrm{RxTh}$.

For $m = 3$:

$$1-\frac{1}{\Gamma(m)}\gamma(m,t)=1-\frac{1}{2}(2\gamma(2,t)-t^2\mathrm{e}^{-t})= \\ 1-\frac{1}{2}(2(\gamma(1,t)-t\mathrm{e}^{-t})-t^2\mathrm{e}^{-t})= \\ \mathrm{e}^{-t}(1+t+\frac{1}{2}t^2). \tag{A6}$$

For $m = 1.5$:

$$1-\frac{1}{\Gamma(m)}\gamma(m,t)=1-\frac{2}{\sqrt{\pi}}(\frac{1}{2}\gamma(\frac{1}{2},t)-t^{\frac{1}{2}}\mathrm{e}^{-t})= \\ 1-\frac{2}{\sqrt{\pi}}(\frac{1}{2}\sqrt{\pi}erf(\sqrt{t})-t^{\frac{1}{2}}\mathrm{e}^{-t})= \\ 1-erf(\sqrt{t})+\frac{2}{\sqrt{\pi}}t^{\frac{1}{2}}\mathrm{e}^{-t}. \tag{A7}$$

Here erf is the error function, its approximation is given by

$$erf(x)\approx\frac{x}{|x|}\sqrt{1-\exp(-x^2\frac{\frac{4}{\pi}+ax^2}{1+ax^2})} \tag{A8}$$

where

$$a=\frac{8(\pi-3)}{3\pi(4-\pi)}\approx 0.140012 \tag{A9}$$

For $m = 1$:

$$1-\frac{1}{\Gamma(m)}\gamma(m,t)=1-\gamma(1,t)=\mathrm{e}^{-t}. \tag{A10}$$

By applying $t = \frac{m}{\Omega}\mathrm{RxTh}$ and (8) to (A6), (A7), and (A10), we obtain the expected packet delivery ratio at distance d.

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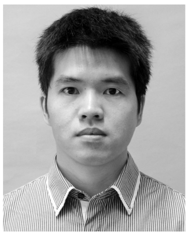

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