A Topology-Aware Reliable Broadcast Scheme for Multidimensional VANET Scenarios

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Abstract. In Vehicular Ad-Hoc Network (VANET), fast and reliable emergency message dissemination among vehicles on the road has positive significance. Besides, the topology of VANET is dynamic and we need to consider the adaptability of message dissemination scheme to different scenarios. By studying the relation between reliable broadcast scheme and different effect factors, we improve the equation of contention window. To meet the needs of multidimensional scenarios, we propose a novel topology-aware broadcast scheme. Each node monitors its neighbors' state according to a FSM (finite-state machine) and transmits the information to proper nodes. The advantages of our scheme are that it enhances the transmission reliability in multidimensional scenarios and improves self-adaptability in dynamic VANET with low propagation latency. By evaluating the proposed solution, our scheme is implemented and simulation results are provided.

Keywords: VANET · Topology-aware · FSM · Self-adaption

1 Introduction

As a special type of Mobile Ad-hoc Network (MANET), VANET is a technology which uses moving cars as nodes. It helps us deliver emergency messages timely to reduce the probability of traffic accidents. However, due to the dynamic topology of the whole vehicle network, speedy movements of the nodes and high drop rates of the channel, new challenges raise in VANETs to broadcast messages reliably and rapidly. Aiming for overcoming these obstacles, we are supposed to design specialized schemes which can greatly improve the performance of VANET.

Vehicles in VANET can broadcast messages and communicate with other vehicles using IEEE 802.11p [1]. These vehicles always need to listen to their neighbors' state by exchanging short messages called beacons. Information inside a beacon may include vehicle's speed, location etc. As the beaconing load may saturate the capacity of the channel, channel congestion should be avoided as

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much as possible. In the broadcast scheme, the sender broadcasts an emergency message, other node who receives this message may be selected as forwarders.

What's more, in a real VANET scenario, the vehicles seldom move on a simple straight road, as there are always complex traffic routes, such as intersections (two-dimensional scenarios) [2] and flyovers (three-dimensional scenarios). A well-designed scheme should take full consideration of these scenarios.

The contributions of this paper are listed as follows:

– We design a FSM (finite-state machine) to help nodes monitor the states of each neighbor and they can make the corresponding decision based on the above information. This scheme improves the reliability of message dissemination in multidimensional VANET scenarios.
– We use a real-time prediction model to help vehicles dynamically optimize the rate of beacons. This scheme can minimize the channel occupancy time and reduce the messages collision.
– We take into full account the influence of node density, distance and channel quality in broadcasting process. The proposed scheme always selects an optimal node as the forwarder and it can fit to different scenarios.

The rest of this paper is organized as follows. In Sect. 2, we survey the related works. In Sect. 3, we point out the design of contention window model and beacon rate model. In Sect. 4, we elaborate the design of our proposed scheme. In Sect. 5, detailed theoretical analysis of the broadcasting scheme is presented. Section 6 describes the simulation environment and the results. Section 7 concludes the paper.

2 Related Work

Without considering the assistance of Road Side Units (RSUs) [3], the schemes in VANET can be categorized into two classes. One is based on senders' policy called sender-oriented approach, the other one is receiver-oriented approach which is based on receivers' policy.

The sender-oriented schemes make the sender decide which neighbor(s) would be chosen as forwarder(s) according to the network topology. This kind of schemes, proposed by Liu et al. [4] and Amoroso et al. [5], are able to rebroadcast message timely when the forwarders catch the rebroadcast instructions. The scheme proposed by Li et al. [6] selects the farthest node as forwarder for fast propagation, however, due to the high drop rate, packet collision and dynamic topology in VANET, the chosen nodes may not receive the message and lead to mistakes. In this case, the sender must modulate and rebroadcast the message until the forwarder sends ACK signals back. Besides, most sender-oriented approaches need to establish a steady connection with forwarders by handshaking. Take the scheme of Khan [7] as an example, which results in noticeable delay. This kind of schemes is highly dependent on beacons to exchange information, which requires the nodes broadcast their beacons frequently. Most of the researchers set a fixed beacon rate to make all the nodes maintain the same topology of the whole network, which may cause the channel collision. What's more, this method can't distinguish multidimensional scenarios, Spaho et al. [2] gives a performance comparison of OLSR and AODV protocols in a Crossroad Scenario, which shows unsatisfactory results. There must be supplementary schemes to cover the shortage.

The receiver-oriented schemes work differently. The sender broadcasts an emergency message to its neighbors firstly, if the neighbors receive the emergency messages successfully, they set up their own timers and broadcast the messages as soon as the timer expires. Based on the above method, the concept of contention window [8,9] is widely used and Reinders et al. [10] analyzes the performance of beacons in VANET. The Receiver-oriented schemes take full advantage of receivers' current position and it is unnecessary to consider network topology changes during the message broadcasting. Voicu et al. [11] propose ACK decoupling mechanism, which eliminates handshaking to realize fast propagation. Suzuki et al. [12] modifies AODV to get minimum end-to-end delay using primary user information and vehicle mobility information. Most of the receiver-oriented schemes don't need complex supplementary information, which reduce the probability of channel collision. However the sender doesn't know its neighbor nodes' state exactly, which leads to the poor performance in multidimensional scenarios.

3 System Model

3.1 Contention Window Model

Contention window (CW) is such as Signal to Noise Ratio (SNR), relative distance(D) [5,6] and vehicle-node density(ρ). Each node i within the transmission range of the sender should calculate its own contention window (CW_i) according to these factors.

SNR is used to quantify the quality of the channel in VANET. Larger SNR value means there are more signal than noise, so it's better to select the receivers with larger SNR as forwarders. We define impact factor of SNR (IF_{snr}) in Eq. (1), where SNR_{thresh} is the minimum threshold, SNR_i is the SNR value of node i and α is the exponential scaling factor.

$$IF_{snr} = \frac{(SNR_i - SNR_{thresh})}{\alpha} \quad (1)$$

In order to transmit the emergency message fast, most researchers [5,6] want to choose the furthest node from the sender as forwarder, which works well in some high-density node scenarios. As Fig. 1 shows, node D can act as an assistant by sending confirmation to prevent further dissemination at T_3 even though A moves out of the sender's broadcasting domain. However, Fig. 2 shows us the problem in low-density scenarios. Node A and B are far away from the sender at T_3, which causes the sender couldn't receive any confirmation. In this case, B is a better choice to forward the message though it's nearer to the sender.

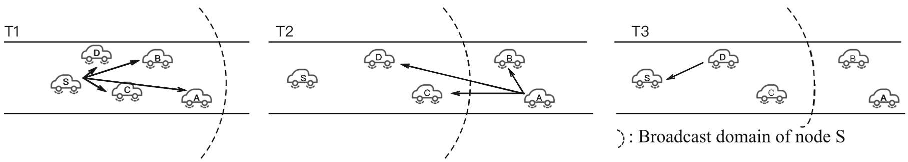

Fig. 1. A high-density nodes model

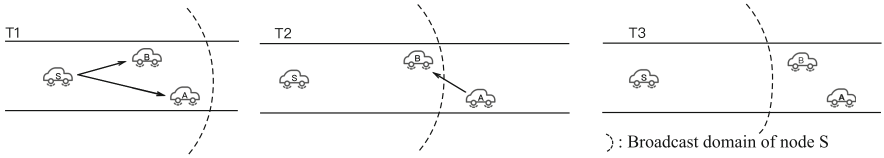

Fig. 2. A low-density nodes model

With regard to the high-density topology, we'd better give priority to the further nodes to make sure the rapid dissemination of messages. In the case of the low-density topology, the nearer node is a better choice to improve reliability in VANET. We define impact factor of position(IF_{pos}) in Eq. (2). In this equation, ρ is the practical density of the sender's neighbors, $\rho \in [0, 1]$. Here D_{max} is the maximum broadcast domain of the sender, D_i is the Euclidean distance between node i and sender and β is the scaling factor.

$$IF_{pos} = \beta(D_i - \rho D_{max})^2 \tag{2}$$

By combining with above factors, contention window of node i can be calculated by Eq. (3). CW_{base} is the minimum size of the size of contention window and k is a scaling factor to keep the contention window in a reasonable range.

$$CW_i = k\frac{IF_{pos}}{IFsnr} + CW_{base} \tag{3}$$

3.2 Beacon Rate Model

We design a dynamic adjustment mechanism based on position prediction. The principle of triggering a new beacon is whether the vehicle's actual position via GPS is identical to the predicted position calculated by the motion model. In order to distinguish whether the prediction is valid, we define a threshold δ. If the difference between predicted and actual position is less than δ, we think it's an effective prediction and there is no need to broadcast a new beacon message. In contrast, a new beacon message will be scheduled to broadcast. As for the neighbors, they will continuously estimate the node's position before receiving an updated beacon.

A vehicle keeps an even speed or various speeds will respectively lead the beacon rate too high or too low. To avoid these problems, we'd better find an infimum and a supremum to limit the range of these beacons. The infimum is associated with the mathematical expectation of contention window ($E[CW]$) which is the expected time that a node have to wait on average before it can broadcast the message. As we focus on whether there are new nodes joining the network rather than the specific position of the neighbor nodes. $E[CW]$ can be calculated in Eq. (4), the infimum and the supreme is defined in (5).

$$E[CW] = \frac{\sum_{i=0}^{total\ nodes} E[CW_i]}{total\ nodes} \approx \frac{\sum_{i=0}^{total\ nodes} \frac{CW_{max,i}}{2}}{total\ nodes} \tag{4}$$

$$B_{inf} = E[CW],\ B_{sup} = 2E[CW] + T_{out} \tag{5}$$

If the time slot between the last beacon and the triggered beacon smaller than B_{inf}, it will schedule the beacon time at B_{inf}. If the time slot bigger than B_{inf} and smaller than B_{sup}, it will broadcast the beacon immediately. Otherwise, it'll schedule the beacon at B_{sup}.

4 Proposed Broadcast Scheme

4.1 Problem Statement

Both the sender-oriented scheme and receiver-oriented scheme have low reliability in multidimensional scenarios. In order to figure out the problem, refer to the model in Fig. 3, vehicle C who is the farthest neighbor of sender (S) is most likely to be chosen as the forwarder.

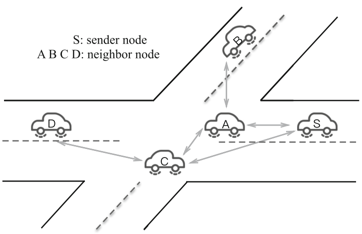

Fig. 3. An intersection scenario.

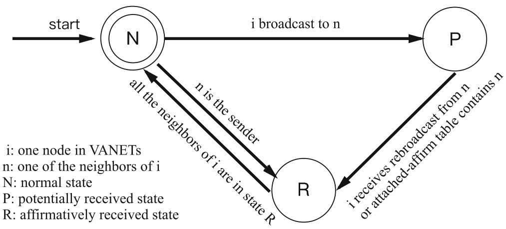

Fig. 4. FSM of node n.

In some contention-window-oriented scheme, C is chosen as the forwarder and broadcasts the message to node A, D and S. According to ACK decoupling mechanism, node S ensures its neighbors have received the message successfully, A cancels its broadcast scheme and B misses this message transmission forever.

4.2 Broadcast Scheme

In one broadcasting process, each node who receives the emergency message will choose a random time slot from the interval $[0, CW_{max}]$ and wait for that period of time. Obviously, the node with the smallest CW_{chosen} wins the chance to forward the emergency message. There is no need for the forwarder to send any extra ACK, because the rebroadcast message acts as an implicit ACK. As soon as the sender receives the same emergency message from others, it considers the emergency message has been forwarded successfully. Due to some accidental factors, the sender may miss the rebroadcast message, it will broadcast again after a timeout period (T_{out}). Upon receiving the same message twice from one sender, a node in the vicinity of both the source and the forwarder will broadcast to the original sender to cancel any further rebroadcasts.

To improve the reliability of broadcasting, in our scheme, each node should listen to beacons which helps to establish a neighbor table and the topology can also be estimated. The neighbor node is subject to a FSM, as Fig. 4 shows. We use node i and its neighbor node n as an example, normal state(N) means i deems n does not receive the emergency messages, potentially received state(P) means i doesn't promise n has received the emergency message and affirmatively received state(R) means i confirms that n has received the emergency message successfully. We conclude the process that node i broadcasts an emergency message in Algorithm 1 and the process that node i receives an emergency message from others in Algorithm 2.

Algorithm 1. Node i broadcasts an emergency message.

Input:
The neighbor table of node i, NT_i;
Output:
The affirm table of node i, AT_i;

for each node $n \in NT_i$ **do**
  if n.state == R **then**
    add n to AT_i;
  else if n.state == N **then**
    turn n into P state;
  end if
end for
broadcast the emergency message and AT_i;

5 Analysis

5.1 Average Per-hop Convergence Time

Average convergence time per-hop is a measure of how fast an emergency message is received by all the sender's neighbors. This performance indicator plays an important role in VANET, and it can speed up convergence.

In the emergency message forwarding process, nodes do not interfere with each other and emergency messages broadcasting is an independent event. According to a bi-dimensional Poisson process with the parameter $\hat{\lambda}$ ($\hat{\lambda} = \frac{\lambda}{E[CW]}$,

Algorithm 2. Node i receives an emergency message from node s.

Input:
The affirm table of node s, AT_s; The neighbor table of node i, NT_i;
s.state = R;
for each node $n \in AT_s$ **do**
  if n $\in NT_i$ **then**
    n.state = R;
  end if
end for
if ever node in NT_i is in R state **then**
  turn them into N state;
else
  caculate the contention window CW_i;
  select a time slot CW_{select} randomly in $[0, CW_i]$;
  while $currenttime == CW_{select}$ **do**
    turn to algorithm 1;
  end while
end if

λ is the average number of nodes per hop), we are going to talk about the probability of collision based on Poisson distribution model. We define event S to be the successful broadcasting process, and the number(n) of messages at a particular time-slot (t) is one ($n = 1$), the probability of S can be expressed as Eq. (6). Similarly, the number of vehicles appearing at a certain place is subject to Poisson distribution. We define event F as having no forwarders in the sender's broadcast domain and the calculation method is given in Eq. (7).

$$P(S) = \frac{\hat{\lambda}^1 e^{-\hat{\lambda}}}{1!} = \hat{\lambda}^1 e^{-\hat{\lambda}} \tag{6}$$

$$P(F) = \frac{\hat{\lambda}^0 e^{-\hat{\lambda}}}{0!} = e^{-\hat{\lambda}} \tag{7}$$

Therefore, the average number of occurrences in the case of event S can be calculated by the mathematical expectation($E\,[S]$), and the details are given by Eq. (8).

$$E[S] = \sum_{i=1}^{\infty} [1 - P(S)]^{i-1} P(S) i = \frac{1}{P(S)} \tag{8}$$

Note that T_{out} is the time out value in a broadcasting process. Finally, the expression for mean per-hop rebroadcast latency is shown in Eq. (9)

$$T_{per} = P(F) T_{out} + [1 - P(F)][\frac{t}{P(S)}] \tag{9}$$

5.2 Average Per-hop Throughput

Average throughput per-hop reflects the payload size of the channel in a broadcasting process. In order to make our scheme work properly, the minimum bandwidth guarantee is required. We expect the scheme exchanges a small amount of data in the broadcasting process.

Assume that the certain payload size of an emergency message is S_{em}, the payload size of a beacon message is S_{bm}. Beacons have the characteristic of memoryless, and they are subject to exponential distribution ($B_{slot} \sim E(\lambda_b)$), as Eq. (10) shows,

$$f(B_{slot}) = \begin{cases} \lambda_b e^{-\lambda_b B_{slot}} & B_{slot} \geq 0 \\ 0 & B_{slot} < 0 \end{cases} \tag{10}$$

We limit the infimum and supremum of beacons in Eqs. (4) and (5) and we can calculate the interval between two adjacently beacons by using mathematical expectation of beacons in Eq. (11).

$$\begin{aligned} E(B_{slot}) &= \int_0^{\infty} B_{slot} f(B_{slot})\, dB_{slot} \\ &= B_{inf} + \frac{e^{-\lambda_b B_{inf}} - e^{-\lambda_b B_{sup}}}{\lambda_b} \end{aligned} \tag{11}$$

For one node in a broadcasting process, it receives $\frac{T_{per}}{E[B_{slot}]}$ times of beacons from one neighbor and finally, the expression for mean per-hop throughput is:

$$Throughput = \frac{\frac{\lambda T_{per}}{E(B_{slot})} S_{bm} + S_{em}}{T_{per}} \tag{12}$$

6 Performance Evaluation

We have set up a variety of scenarios to test the performance of the proposed broadcasting scheme. The simulation is performed in The Network Simulator (ns-3), version 3.26 and Simulation of Urban Mobility (sumo), version 0.30. Ns-3 is a discrete-event network simulator and we implement our broadcasting scheme with it. Sumo can simulate the real scene of VANET, we use it to generate 2D layout scenarios. In simulation, our scheme is compared with Abbasi's scheme [11] and Lu's scheme [13]. Table 1 lists the basic parameters used in our simulation.

Figure 5 shows the broadcast simulation results in a 2D scenario, the average per-hop delay reflects the performance of broadcasting speed. Note that for lower node density, the average per-hop delay is pretty high. The reason for this phenomenon is that these vehicles have to wait for a timeout slot before rebroadcast. Benefiting from the interactions between the density of the nodes and the size of the contention window, our proposed scheme can select the best message forwarder in a low node density scenario. In this way, our proposed scheme has a better performance in sparse scenarios and has a flat performance with others in dense scenarios.

In Fig. 6, we analyze the collision rate which indicates the percentage of the packet transmission failure. Due to the beacon messages in our proposed

Table 1. Simulation parameters

Attribute	Value
Data rate	1 Mbps
Transmission range	200 m
Total number of nodes	200 nodes
SNR_{thresh}	30 dB
Packet size	40 bytes
Vehicular speed	120 kmph
Propagation loss model	Nakagami propagation loss model
Mobility model	Sumo 0.30
Unit interval	1 ms

scheme, there are more messages to broadcast than other two scheme in a sparse scenario. In contrast to the dense scenarios, our scheme decreases the number of rebroadcasts and maintains the collision rate in an acceptable level. It represents that these messages have a greater possibility to be transmitted successfully.

In order to determine how many vehicles can receive the emergency message during one broadcasting process, we use reception ratio as a measurement. For 1-D scenario, we simulate in a highway model. For 2-D scenario, we use a grid model to simulate. What's more, we use the road model of New York City and Shanghai City to simulate realistic scenarios. Figure 7 shows the reliability of the proposed scheme in different scenarios. As we can see, our proposed scheme performs better in complex scenarios, which profits from the novel acknowledgement mechanism. Packet loss occurs frequently in the other two schemes because of the changing topology of vehicles. Hence our proposed scheme has a higher reliability in emergency messages broadcasting.

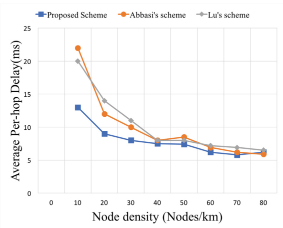

Fig. 5. Average per-hop delay under different vehicle densities

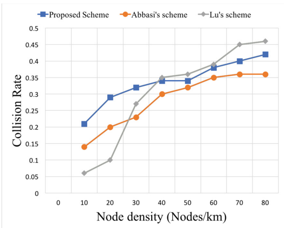

Fig. 6. Average collision rate under different vehicle densities

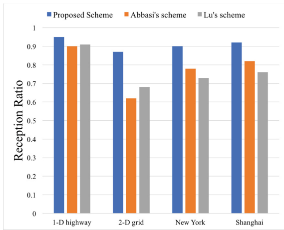

Fig. 7. Reception ratio of various scenarios

7 Conclusion

The proposed scheme gives full consideration to position, SNR and nodes density. The acknowledgement mechanism using neighbor table guarantees the scheme can achieve higher reliability. The simulation results indicate the performance of the proposed scheme is better than the compared schemes in multidimensional and complex VANET scenarios. In the future work, real world implementation to measure the performance of our proposed scheme in 3D VANET scenarios will be executed.

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