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SPECIAL ISSUE PAPER

A cooperative offloading game on data recovery for reliable broadcast in VANET

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SUMMARY

The rapidly growing demand for accident-free driving in intelligent transportation makes reliable broadcast a critical factor for vehicular *ad hoc* networks. Existing solutions always try to improve the broadcast reliability by retransmitting lost packets. However, the excessive retransmissions can easily cause unpredictable time delay and even broadcast storms, rendering the reliable broadcast problem unsolved. In this paper, a novel reliable broadcast scheme is proposed by exploring the advantages of lost data piggybacking. Our scheme allows all the vehicles to piggyback some received packets cooperatively to help other vehicles to recover the lost packets. We formulate the cooperative piggybacking problem as a cooperative offloading game and present a decentralized solution to compute the optimal data piggybacking solutions based on only partial network information. A reward-penalty scheme is designed for the offloading process to impel all the vehicles' decisions that converge to the Nash equilibrium, which is proved to be the global optimal solution to the decentralized offloading scheme. Simulation results show that the proposed cooperative offloading scheme can achieve much higher broadcast reliability and lower propagation delay, in comparison with existing solutions. In a small vehicle network, all lost cooperative awareness messages can be successfully recovered within 25 ms after the initial broadcast by using the data traces generated by GEMV^2. Copyright © 2016 John Wiley & Sons, Ltd.

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KEY WORDS: cooperative offloading; data piggyback; Nash equilibrium; reliable broadcast

1. INTRODUCTION

Recently, much attention has been paid to intelligent transportation systems in both academia and industry to develop efficient solutions to improve driver/vehicle safety and transportation efficiency. Vehicular *ad hoc* networking is one of the most promising technologies in achieving these goals and has become a key component of intelligent transportation systems. A vehicular *ad hoc* network (VANET) is a mobile wireless network that consists of self-organized on-road vehicles, in which vehicles can exchange and share the traffic information via vehicle–vehicle (V2V) and vehicle–infrastructure communications [1–3]. To assist drivers to improve driving safety, the OSI/ETSI and IEEE 802.11p require that each vehicle should broadcast a heart beat message called the cooperative awareness message (CAM) periodically to share its current status (e.g., location, speed, and direction) with adjacent vehicles to improve the safety on wheels [4–6]. With this exchanged information, the driver's perception range can be significantly extended. Based on the timely information

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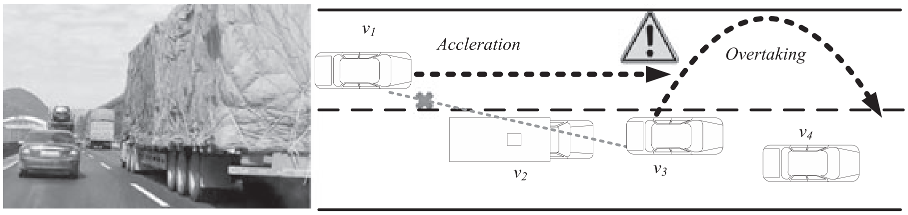

(*a*) (*b*)

Figure 1. The body of large vehicles blocks the signals.

of the road environment and the action of the neighboring vehicles, for example, following distance, and intention to accelerate, decelerate, or overtake, the driver can take instant actions to prevent accidents.

If each vehicle can reliably and timely receive the CAMs' broadcast by neighboring vehicles, the road safety can be significantly enhanced. However, in real circumstances, the wireless channel for V2V communications is unreliable, and packets may frequently get lost because of signal blocking and reflection caused by nearby vehicles and buildings. For example, as illustrated in Figure 1(a), the body of large vehicles can block the communication signals and result in unreliable broadcast [7–9]. Some related experiments were carried out by Wu *et al.* to investigate the reliability of V2V communications with a 2.5 dB omni-directional external antenna placed on the roof of the vehicle in [10], and the experimental results show that there exist frequent dips in the receive ratio even if there is no obstructions between the sender and receiver, and any geometry of the road (e.g., curves) and obstructions (e.g., trees) can result in dramatical drops in the broadcast reliability. The situation becomes even worse in bad weathers, for example, foggy and raining due to severe signal reflection/refraction caused by the raindrops and particles in the fog [11–13].

It is worth noting that any packet loss in CAM broadcast may cause potential accidents as the lost CAMs might contain important traffic information on hidden risks. For example, in extreme weathers such as fast-moving fogs and rainstorms, the visibility may drop dramatically, which can cause blurred visions and even blindness in vehicles. In this situation, the loss of some important CAMs can result in serious accidents as the potential risks are hard to be perceived through vision. As illustrated in Figure 1(b), v_3 cannot hear from v_1 as the channel link is blocked by a truck v_2. This can lead to serious crash if v_3 overtakes without awareness of v_1's acceleration in the foggy weather. Hence, it is crucial to guarantee the reliability of CAM broadcast in VANETs.

Existing schemes on enhancing broadcast reliability can be broadly grouped into three categories: (1) *source-based retransmission* [14–16]: Any vehicle that fails to receive a CAM simply requests the source vehicle to rebroadcast the lost CAM. This scheme is simple but not very efficient because packet loss is commonly bursty in wireless channels. If the current packet is lost, there is a large probability for the retransmitted data to be lost again over the same channel. (2) *Flooding-based retransmission* [17–19]: Any vehicle that fails to receive a CAM broadcasts a request. All vehicles that receive the request and have a copy of the lost CAM simply rebroadcast the lost CAM. Flooding-based schemes are more robust in the presence of unreliable wireless links. However, frequent packet losses will lead to a huge number of CAM rebroadcasts, causing broadcast storms, congested channel, and unpredicted propagation delay [20]. (3) *Forwarder-based retransmission* [21–23]: For each lost CAM, an optimal forwarder will be selected to retransmit it based on metrics such as Global Position System (GPS) positions and channel link quality. This scheme can reduce the risk of broadcast storm, but it calls for the global information and central control of the network to find out the optimal forwarder, which is difficult in highly dynamic networks.

In this paper, we propose an efficient scheme to recover the lost packets in CAM broadcast by formulating the data recovery problem as a cooperative offloading game and exploring the advantage of data piggybacking. To achieve a cooperative recovery of the lost packets, all the vehicles play a cooperative offloading game, in which the task of recovering each lost CAM is offloaded onto one vehicle or several vehicles through data piggybacking, that is, each vehicle is allowed to piggyback some received data in its routine broadcast messages to help other vehicles recover the lost data.

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The objective is to recover all the lost packets through the cooperative offloading game, and all the vehicles can achieve a global equilibrium with high broadcast reliability and low delay. The major challenge here is how to cooperatively offload the tasks in data recovery in the decentralized way to maximize the broadcast reliability, that is, finding out an optimal solution on which lost CAM should be piggybacked by which vehicle in the cooperative offloading to maximize the broadcast reliability in VANETs.

The main contributions of this work are summarized as follows:

- We proposed a cooperative offloading game for lost CAM recovery in VANET, in which each vehicle cooperates with its neighbors to piggyback some received CAMs to help other vehicles recover their lost CAMs.
- We designed a reward–penalty algorithm (RPA) to impel all vehicles' piggyback decisions to converge to the global optimal solution; otherwise, it can be trapped in the local optimum as each vehicle only has partial information in the decentralized piggyback process.
- We proved that the Nash equilibrium is the global optimal solution in the cooperative offloading scheme and established a lower bound and an upper bound on the convergence time.
- We evaluated the cooperative offloading scheme through simulations using real traces and compared its performance with other schemes. Simulation results show that all the vehicle's piggyback decisions converge to the global optimal solution with a higher reliability in comparison with other two existing solutions. All the lost CAMs can be recovered and received successfully in 71.8 ms even in a cooperative offloading game with 16 vehicles, which is still much less than the requirement (100 ms) in the OSI/ETSI.

The remainder of this paper is organized as later. Several related solutions on enhancing broadcast reliability are reviewed in Section 2. Motivations and design challenges are presented in Section 3. Section 4 gives the network model and the problem of broadcast reliability. Section 5 describes the cooperative offloading scheme to recover the lost data, in which a reward–penalty scheme is adopted to supervise all the vehicles to make a cooperative piggybacking. In Section 6, simulation results are presented and discussed, and the conclusions are drawn in Section 7.

2. RELATED WORK

There are extensive studies in the literature on recovering lost packets in wireless transmissions. However, existing solutions always suffer from the tradeoff between enduring heavy communication overhead because of excessive retransmissions and compromising poor reliability with limited number of retransmissions to avoid broadcast storms. In [24], a flooding scheme based on time division multiple access (TDMA) was proposed for reliable broadcast, in which the time taken to flood the message to the network is bounded to a fixed duration (one frame). The simulation results show that this scheme can achieve low broadcast delay, but it cannot significantly improve broadcast reliability as there are too many data collisions in each flooding period. The excessive packet duplications in the flood can also cause a heavy overhead in the network. In [25], Chiu proposed a novel flooding scheme based on received signal strength, which combines probability-based and location-based flooding algorithms to reduce the number of retransmissions. Even though the number of duplicated retransmissions can be reduced to some extent in this scheme, there still exists a high probability of data collision at the receiving node caused by the concurrency retransmission in the flooding algorithm. Lou *et al.* presented a double-covered broadcast algorithm in the mobile *ad hoc* networks to overcome the broadcast storm problem in [26], which increases the broadcast reliability via redundancy coverage by selecting cooperative forwarding node. However, they assume that the lost data can be recovered successfully at the receiver once the source overheard the forwarding message, which is not always true in real circumstances.

Another group of closely related work is the use of the learning-based method to enhance broadcast reliability. In [27], Liu *et al.* proposed a receiver consensus-based approach for forwarder selection. The vehicle nearest to the ideal forward position will be selected based on geographic information. The drawback is that each vehicle has to dynamically maintain global geographic

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information of all the vehicles in the VANET, and it also calls for a central controller to make the forwarder selection decisions, which is difficult in highly dynamic networks. In [28], a task-sharing (information) scheme in a distributed network was proposed by Sharma *et al.*, aiming to recover all the shared information at each node. A global solution at Nash equilibriums via centralized control and a large quantity of manager–client interactions in the network was proposed. However, the highly centralized control by a network manager is difficult and even impossible in complex networks, not to mention the VANET that consists of a large number of vehicles with high mobility. Lauer *et al.* focuses on a distributed Q-learning algorithm for multi-agent decision systems in which the autonomous agents with different utility functions make decisions cooperatively to maximize the global reward of the system [29]. However, the iterations in the data training step make the distributed Q-learning more like a brute force approach. More importantly, this algorithm cannot be transferred to stochastic Markov Decision Processes (MDPs) because of an indeterministic transition rule.

Although extensive studies have been carried out to improve broadcast reliability and to reduce communication overhead, including duplication-based coverage, coalition formation game, and Q-learning, the problem of decentralized cooperative lost data recovery in complex networks still remains an open problem. This paper presents a new broadcast scheme to increase the reliability of CAM broadcast in VANETs via data piggybacking. To the best of our knowledge, it is the first time that cooperative piggybacking is used to address the reliable broadcast problem in VANETs.

3. MOTIVATION AND SYSTEM MODEL

3.1. Motivation

Due to the lossy wireless channel and the highly dynamic mobility of vehicles in a VANET, there might be many CAM losses in the V2V communications. To recover the lost CAMs for high broadcast reliability, traditional schemes tend to request either the source vehicle or the vehicle(s) that successfully received the lost CAM to rebroadcast it before its time to live (TTL). However, the problem is that the lost CAM rebroadcast will always introduce extra communication overhead besides the routine communications, which will make the wireless channel congested.

Another major concern is secure communication in VANETs. To provide secure communication, the elliptic curve digital signature algorithm is employed for authentication in the IEEE 1609.2 standard [30]. The data payload that contains state information is only 53 bytes, whereas the certificate and signature used for authentication take up 209 bytes, which leads to a packet size of up to 262 bytes. If the state information can be somehow piggybacked in the routine broadcast messages, the communication goodput can be significantly improved. For example, if each vehicle is allowed to piggyback the state information received from another two vehicles to recover lost CAMs, the maximum packet size will be $209 + 53 \times (1 + 2) = 368$ bytes, but the goodput will be enhanced by 114%. Also, the propagation delay can be reduced, and the broadcast storms could be avoided in comparison with existing retransmission-based solutions. Based on this observation, we propose a decentralized cooperative offloading scheme to enhance the broadcast reliability by exploiting the advantage of CAM piggyback. The term *cooperative* can be comprehended as each vehicle can cooperate with other vehicles to select the CAMs to be piggybacked and piggybacks them within its own routine data in the periodical broadcast, with the objective to maximize the number of recovered lost CAMs.

The key question is how to decide which vehicle should piggyback that lost CAM. There are at least two harsh conditions that should be considered:

(1) Most of the vehicles can only acquire partial information of the network topology and channel quality because of the unstable and unreliable channel links. Each vehicle can make piggybacking decision based solely on this partial local information.
(2) The CAM broadcast is not delay tolerant, especially for the situations that the lost CAMs contain important information such as emergent crashes and overtaking. Hence, the lost CAMs need to be recovered as quickly as possible.

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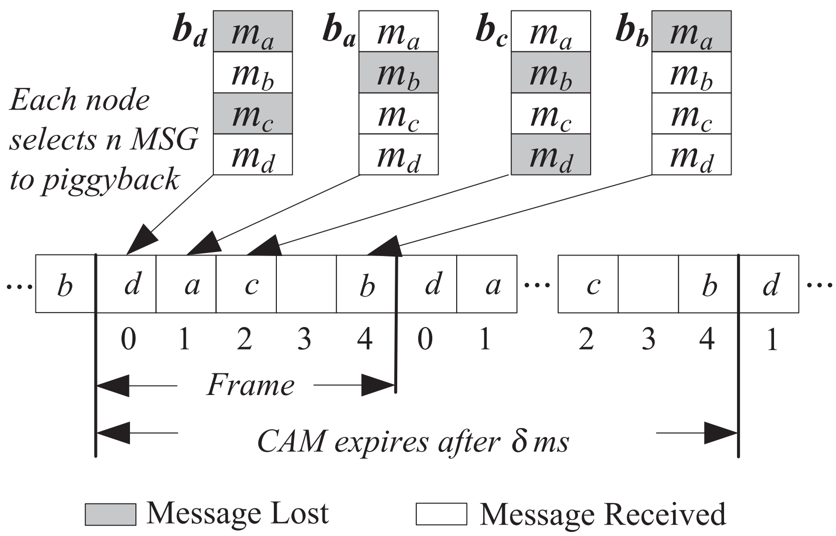

Figure 2. Piggyback cooperative awareness messages (CAMs) in the vehicular *ad hoc* network.

Considering the aforementioned conditions, the reliable broadcast problem can be regarded as a decentralized cooperative data-recovery offloading game, in which each vehicle should select and piggyback some received CAMs distributively and cooperatively with the purpose of recovering all the lost CAMs before the TTL to maximize the broadcast reliability. In other words, the following questions should be answered in the cooperative offloading game: (1) Which vehicle should be selected for piggybacking? (2) Which lost CAM should be piggybacked if there is a constraint on the maximum number of piggybacked CAMs? (3) How to cooperate with others to maximize the broadcast reliability with only partial local information?

3.2. System model

Let $V = \{v_1, v_2, \ldots, v_m\}$ be the m vehicles in a VANET. We define RoI_i as v_i's region of interest (RoI) with r_i ($r_i \leqslant m$) vehicles inside. Assume that these r_i vehicles inside RoI_i have significant impact on v_i's safety, such as emergent brakes and overtaking, and v_i should reliably receive the CAMs broadcast by these vehicles in real time. We also assume that RoI_i is smaller than v_i's broadcasting coverage, which implies that CAM losses mainly result from the unstable and unreliable wireless channel due to signal blocking and other background noises in the traffic.

The IEEE802.11p standard, which is also referred as the dedicated short range communications standard, uses the 5 GHz frequency spectrum that is divided into one control channel and six service channels. The control channel is mainly used for the transmission of safety-critical messages, while the service channels are used for both safety and non-safety communications. In this paper, we assume that each vehicle uses the control channel to broadcast CAMs. To coordinate the access of the control channel, we adopt a self-organized time division multiple access (STDMA) setup, as illustrated in Figure 2. It has been demonstrated that STDMA can achieve faster schedule reconfiguration than TDMA and more predictable communication delay in comparison with IEEE 802.11p, especially in the presence of vehicle crowding and broadcast storms [31–33]. Each vehicle periodically broadcasts CAMs, and the time interval between CAM generation should be no larger than 100 ms, as suggested by the ETSI standard [34].

3.3. Problem formulation

Suppose $RC_i = \{cam_1, cam_2, \ldots, cam_n\}$ are the n CAMs that v_i received from other vehicles, and each v_i keeps a buffer b_i to cache the received CAMs. Assume that each time v_i broadcasts its own CAM, it can select to piggyback at most w CAMs from b_i. By introducing a decision variable,

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$$d_{ij} = \begin{cases} 1, & \text{if } cam_j \text{ is piggybacked by } v_i, \\ 0, & \text{if } cam_j \text{ is not piggybacked by } v_i, \end{cases} \tag{1}$$

we define the vector $\boldsymbol{f}_i$=$[d_{i1}, d_{i2}, \ldots, d_{in}]$ where $\sum_{j=1}^{n} d_{ij} \leqslant w$ as a feasible piggyback decision that v_i can make in the cooperative offloading game, the combination of all the feasible piggyback decisions, that is, $\mathbb{F}_i = \left\{ \boldsymbol{f}_i | \sum_{j=1}^{n} d_{ij} \leqslant w \right\}$, is defined as v_i's feasible decision space, and the combination of each vehicle's piggyback decision, that is, $\boldsymbol{F} = \{\boldsymbol{f}_1, \boldsymbol{f}_2, \cdots \boldsymbol{f}_m\}$, is the joint decision of all the vehicles in the cooperative offloading game.

We assume that a received CAM cached in a vehicle's buffer is valid until its TTL expires or a new generated CAM arrives, and the feasible decision space $\mathbb{F}_i$ is also fixed during this time of interest. Then the individual objective at each vehicle and the global objective for the data offloading game are defined in Eqs. (2) and (3), respectively.

$$\max u_i(\boldsymbol{f}_i) = \frac{N_{ir}(\boldsymbol{f}_i)}{N_i}, \quad s.t. \quad \boldsymbol{f}_i \in \mathbb{F}_i, \tag{2}$$

$$\max U(\boldsymbol{F}) = \sum_{i \in V} u_i(\boldsymbol{f}_i) = \sum_{i \in V} \frac{N_{ir}(\mathbf{F})}{N_i} \quad s.t. \quad \boldsymbol{f}_i \in \mathbb{F}_i, \boldsymbol{F} = \{\boldsymbol{f}_1, \boldsymbol{f}_2, \ldots, \boldsymbol{f}_m\}, \tag{3}$$

where N_i is the total number of vehicles that are interested in v_i's CAM and $N_{ir}(\boldsymbol{F})$ is the number of vehicles that can receive the CAMs reliably under the joint decision $\boldsymbol{F}$.

In this paper, we aim to find out an optimal solution $\boldsymbol{F}$ that can offload the data recovery cooperatively and improve the broadcast reliability in the VANET, that is, maximize the individual objective function in Eq. (2) and the global objective function in Eq. (3).

4. COOPERATIVE OFFLOADING GAME

In this section, we transform the cooperative piggyback problem presented in Section 3.3 into a cooperative offloading game based on a RPA and prove that solving the cooperative piggyback problem is equivalent to solving the cooperative offloading game formulated in this section.

Our cooperative offloading game is formulated based on an RPA, which is used to supervise all vehicles to reach a consensus on how to make a cooperative offloading on data recovery. The key idea is that each vehicle should learn from other vehicle's decisions in the piggyback process. The less deviation between v_i and other vehicles' decisions, the more rewards and less penalties that v_i will receive. The cooperative offloading with RPA is described as follows:

(1) Each vehicle v_i sends out a proposal, including a set of suggestions to all the vehicles in its ROI_i. The suggestion is defined as a recommendation on which CAM v_i expects other vehicles to piggyback. Each suggestion is associated with a credit. The higher the credit is, the higher priority the suggested CAM is supposed to be piggybacked.
(2) As different vehicles may lose different CAMs, the credit for the same CAM varies in different vehicles' proposals. To achieve an optimal solution, each vehicle should overhear other neighbors' proposals and learn from both suggestions and credits before making its own piggyback decision. The larger the deviation between v_i and its neighbors' proposal, the more penalties and less rewards v_i will receive.

We use g_{ij} to represent the suggestion from v_i to its neighbor v_j on which CAM(s) it expects v_j to piggyback, and c_{ij} is the corresponding credit that v_i offers for this suggestion. Then we use $\boldsymbol{g}_i = \left\{g_{i1}, g_{i2}, \ldots, g_{ir_i}\right\}$ to represent the joint suggestion from v_i to all the vehicles in ROI_i, and $\boldsymbol{c}_i = \left\{c_{i1}, c_{i2}, \ldots, c_{ir_i}\right\}$ as the joint credit that v_i offers for $\boldsymbol{g}_i$. We define the combination of $(\boldsymbol{g}_i, \boldsymbol{c}_i)$ as v_i's proposal, denoted by $\boldsymbol{P}_i$, in the cooperative offloading game. Essentially, $\boldsymbol{P}_i = (\boldsymbol{g}_i, \boldsymbol{c}_i)$ implies v_i's own desire on lost CAMs, as the more v_i requests in g_{ij}, the higher credit it will offer in c_{ij}.

DOI: 10.1002/cpe

To make an accurate calculation of the deviation between different proposals, we use $\nabla_i = (\boldsymbol{c}_{i+1} - \boldsymbol{c}_i) + (\boldsymbol{g}_{i+1} - \boldsymbol{g}_i)\text{diag}(\boldsymbol{c}_i)(\boldsymbol{g}_{i+1} - \boldsymbol{g}_i)^T$ to represent the deviation of v_i's proposal from that of v_{i+1}. As $\boldsymbol{g}_i$ implies v_i's desire on lost CAMs and $\boldsymbol{c}_i$ indicates v_i's expectation on other vehicles' help, the deviation ∇_i can be regarded as how much v_i's proposal $\boldsymbol{P}_i$ can satisfy v_{i+1}'s request for lost CAMs. The smaller ∇_i is, the more v_{i+1} is satisfied with v_i's proposal.

$$\begin{aligned} rp_i &= \nabla_{i+1} - \nabla_i \\ &= \left[(\boldsymbol{c}_{i+2} - \boldsymbol{c}_{i+1})(\mathbf{1})^T + (\boldsymbol{g}_{i+2} - \boldsymbol{g}_{i+1})diag(\boldsymbol{c}_{i+1})(\boldsymbol{g}_{i+2} - \boldsymbol{g}_{i+1})^T\right] \\ &\quad - \left[(\boldsymbol{c}_{i+1} - \boldsymbol{c}_i)(\mathbf{1})^T + (\boldsymbol{g}_{i+1} - \boldsymbol{g}_i)diag(\boldsymbol{c}_i)(\boldsymbol{g}_{i+1} - \boldsymbol{g}_i)^T\right]. \end{aligned} \tag{4}$$

We define rp_i in Eq. (4) as the rewards ($rp_i > 0$) or penalties ($rp_i < 0$) for each vehicle v_i according to the deviation between different proposals:

(1) If $rp_i > 0$, v_i is rewarded. The less $\boldsymbol{P}_i$ deviates from v_{i+1}'s proposal $\boldsymbol{P}_{i+1}$, the more v_{i+1} is satisfied, and the more rewards v_i are received.
(2) If $rp_i < 0$, v_i is penalized. The more $\boldsymbol{P}_i$ deviates from v_{i+1}'s proposal $\boldsymbol{P}_{i+1}$, the less v_{i+1} is satisfied, and the more penalties v_i will receive.

By introducing RPA, the individual objective function given in Eq. (2) and the global objective function given in Eq. (3) can be redefined as follows:

$$u_i^*(\boldsymbol{f}_i, \boldsymbol{rp}_i) = u_i(\boldsymbol{f}_i) + \boldsymbol{rp}_i \quad \text{where } \boldsymbol{f}_i \in \mathbb{F}_i, \tag{5}$$

$$U^*(\boldsymbol{F}, \boldsymbol{RP}) = \sum_{i \in V} u_i^*(\boldsymbol{f}_i, \boldsymbol{rp}_i), \tag{6}$$

where $\boldsymbol{RP} = \{\boldsymbol{rp}_1, \boldsymbol{rp}_2, \cdots, \boldsymbol{rp}_m\}$ is the joint reward or penalty corresponding to $\boldsymbol{F} = \{\boldsymbol{f}_1, \boldsymbol{f}_2, \cdots, \boldsymbol{f}_m\}$.

Theorem 1
The global effective-objective function in Eq. (6) is equivalent to the objective function in Eq. (5).

Proof
The difference of these two objective functions is that the RPA is evolved in the global effective-objective function given in Eq. (6) to supervise all the vehicles to make cooperative decisions on data recovery.

$$\begin{aligned} \max\ U^*(\boldsymbol{F}, \boldsymbol{RP}) &= \max \sum_{i \in V} u_i^*(\boldsymbol{f}_i, \boldsymbol{rp}_i) = \max \sum_{i \in V} (u_i(\boldsymbol{f}_i) + rp_i) \\ &= \max \left(\sum_{i \in V} u_i(\boldsymbol{f}_i) + \sum_{i \in V} rp_i \right). \end{aligned} \tag{7}$$

Because all the rewards come from the penalties, the sum of rewards and penalties in the offloading game should be 0, that is, $\sum_{i \in V} \boldsymbol{rp}_i = 0$.

Hence,

$$\max \left(\sum_{i \in V} u_i(\boldsymbol{f}_i) + \sum_{i \in V} rp_i \right) = \max \sum_{i \in V} u_i(\boldsymbol{f}_i) = \max\ U(\boldsymbol{F}). \tag{8}$$

□

Based on Theorem 1, the cooperative offloading game can be formulated as the following optimization problem with the objective of finding an optimal decision $\boldsymbol{F}$ to maximize the global effective-objective function $\mathbb{U}(\boldsymbol{F}, \boldsymbol{RP})$.

DOI: 10.1002/cpe

$$\max\ U^*(\boldsymbol{F}, \boldsymbol{RP}) = \max_{(\boldsymbol{f}_i, \boldsymbol{rp}_i)\in\mathcal{D}} \sum_{i\in V} u_i(\boldsymbol{f}_i, \boldsymbol{rp}_i)$$
$$s.t. \boldsymbol{F} = \{\boldsymbol{f}_1, \boldsymbol{f}_2, \dots, \boldsymbol{f}_m\}, \quad \boldsymbol{RP} = \{\boldsymbol{rp}_1, \boldsymbol{rp}_2, \dots, \boldsymbol{rp}_m\} \tag{9}$$
$$\mathcal{D} = \left\{(\boldsymbol{f}_i, \boldsymbol{rp}_i) | \sum_{i\in V} \boldsymbol{rp}_i = 0,\ \boldsymbol{f}_i \in \mathbb{F}_i, i \in V\right\},$$

where the domain $\mathcal{D}$ is declared to restrict the feasible $(\boldsymbol{f}_i, \boldsymbol{rp}_i)$ for the cooperative offloading problem. Actually, if $(\boldsymbol{f}_i, \boldsymbol{rp}_i) \notin \mathcal{D}$, $u(\boldsymbol{f}_i, \boldsymbol{rp}_i)$ is set to negative infinity, which cannot be the optimal solution to maximize $U^*(\boldsymbol{F}, \boldsymbol{RP})$.

If all the vehicles can acquire the global information such as each vehicle's piggyback decision and the channel reliability, the cooperative offloading game in Eq. (9) can be solved as a simple global optimal problem. However, a real VANET has very dynamic network topology, and most vehicles will suffer from frequent CAM losses, which makes it difficult for each node to get the global information. In the next section, we will present a decentralized solution in which each vehicle makes offloading decisions to solve the decentralized optimization problem in Eq. (9) with only partial information.

5. OPTIMAL COOPERATIVE OFFLOADING

5.1. The cooperative offloading

Assume each vehicle can communicate with at least two vehicles. We divide the vehicles in the VANET into sequenced groups as shown in Figure 3(a), in which any two adjacent groups have at least two overlapped vehicles. Taking the three vehicles in Figure 3(b), for example, all the vehicles can be divided into three sequenced groups as (v_1, v_2, v_3), (v_2, v_3, v_1), and (v_3, v_1, v_2). This group allocation will be used in the rp_i's calculation, and all the vehicles can learn from its neighbors' decisions in the allocated groups and acquire the global information gradually, which can help all the vehicles make an optimal piggyback in the decentralized offloading game.

Based on the group allocation and the basic idea of RPA, the proposed cooperative offloading scheme can be described as follows:

(1) Each vehicle v_i piggybacks its proposal $\boldsymbol{P}_i = (\boldsymbol{g}_i, \boldsymbol{c}_i)$ in its CAMs to exchange local information with other vehicles.
(2) Based on the received proposals, each suggestion on cam_j is counted based on the received suggestions. The more times a CAM is suggested by v_i's neighbors, the higher priority it will be suggested again by v_i. The CAM corresponding to the suggestion from v_i to itself will be piggybacked by v_i.
(3) Each vehicle v_i makes its own proposal based on its own suggestions and calculates the rp_i as described in (10) and (11), respectively.

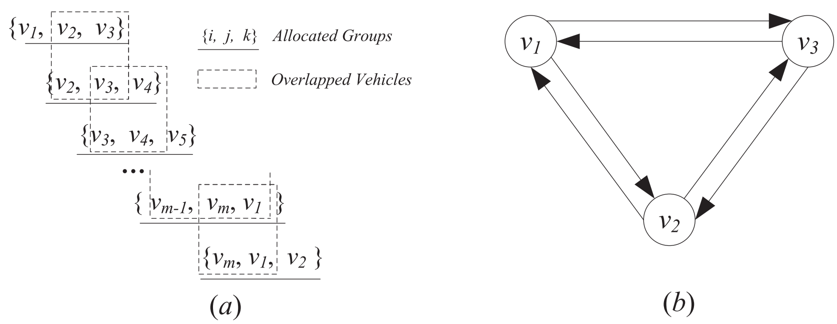

Figure 3. Group allocation.

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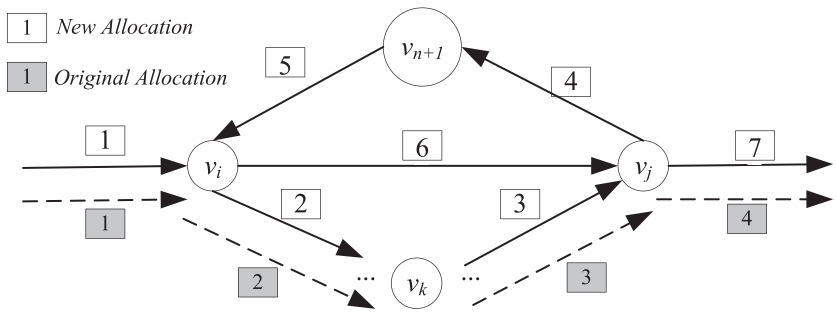

Figure 4. Group allocation.

$$\begin{cases} \boldsymbol{f}_i = \arg\max\ \mathrm{count}(cam_j | cam_j \in RC_i) & (10) \\ \boldsymbol{rp}_i = ((\boldsymbol{c}_i - \boldsymbol{c}_{i+1}) - (\boldsymbol{c}_{i+1} - \boldsymbol{c}_{i+2}))(\mathbf{1})^T \\ \quad + (\boldsymbol{g}_i - \boldsymbol{g}_{i+1})\mathrm{diag}(\boldsymbol{c}_i)(\boldsymbol{g}_i - \boldsymbol{g}_{i+1})^T & (11) \\ \quad - (\boldsymbol{g}_{i+1} - \boldsymbol{g}_{i+2})\mathrm{diag}(\boldsymbol{c}_{i+1})(\boldsymbol{g}_{i+1} - \boldsymbol{g}_{i+2})^T. \end{cases}$$

5.2. Analysis

Theorem 2

All vehicles can be divided into sequenced groups in the form of $\{(v_1, v_2, v_3), (v_2, v_3, v_4), \ldots, (v_m, v_1, v_2)\}$ where $m \geqslant 3$ if each vehicle can communicate with at least two vehicles and the communication links are symmetric.

Proof

For a VANET with three vehicles, the vehicles can be divided into three sequenced groups as $(v_1, v_2, v_3), (v_2, v_3, v_1)$, and (v_3, v_1, v_2).

Suppose a VANET with n vehicles can be successfully divided into sequenced groups as $(v_1, v_2, v_3), \ldots, (v_{i-1}, v_i, v_{i+1}), \ldots, (v_{k-1}, v_k, v_{k+1}), \ldots, (v_{j-1}, v_j, v_{j+1}), \ldots, (v_m, v_1, v_2)$. For a VANET with $(n + 1)$ vehicles, suppose v_{n+1} can communicate with v_i and v_j. Then, the $(m + 1)$ vehicles can be re-allocated as $(v_1, v_2, v_3), \ldots, (v_{i-1}, v_i, v_{i+1}), \ldots, (v_{k-1}, v_k, v_{k+1}), \ldots, (v_{j-1}, v_j, v_{m+1}), (v_j, v_{m+1}, v_i), (v_{m+1}, v_i, v_j), (v_i, v_j, v_{i+1}), \ldots, (v_m, v_1, v_2)$, which is shown in Figure 4. Hence, Theorem 2 holds. □

Another analysis related to the cooperative offloading is the global optimum at the Nash equilibrium. In the cooperative offloading game, each vehicle makes its piggyback decision greedily to maximum the individual object function $u_i^*(\boldsymbol{f}_i, \boldsymbol{rp}_i)$. According to the Nash equilibrium, we define $(\boldsymbol{F}^*, \boldsymbol{RP}^*) = \{(\boldsymbol{f}_1^*, \boldsymbol{rp}_1^*), (\boldsymbol{f}_2^*, \boldsymbol{rp}_2^*), \cdots (\boldsymbol{f}_m^*, \boldsymbol{rp}_m^*)\}$ as the balance point in the cooperative offloading game, where no vehicle wants to deviate unilaterally as it is the optimal response to other vehicles' decisions. However, not all the Nash equilibriums are global optimal as it is a necessary condition rather than a sufficient one for the global optimal problem. In the following, we prove that the Nash equilibrium in the cooperative offloading game is the global optimal solution to the cooperative piggyback problem.

Theorem 3

The Nash equilibrium $(\boldsymbol{F}^*, \boldsymbol{RP}^*) = \{(\boldsymbol{f}_1^*, \boldsymbol{rp}_1^*), (\boldsymbol{f}_2^*, \boldsymbol{rp}_2^*), \cdots (\boldsymbol{f}_m^*, \boldsymbol{rp}_m^*))\}$ in the cooperative offloading game is a global optimal solution to the cooperative piggyback problem given in Eq. (3).

Proof

For the Nash equilibrium $(\boldsymbol{F}^*, \boldsymbol{RP}^*)$ in the cooperative offloading game, there exist no other strategy that can gain a better performance. Hence, for each $i \in \boldsymbol{V}$, we can have inequality.

$$
\begin{aligned}
&U^*(\boldsymbol{F}^*, \boldsymbol{RP}) \leqslant U^*(\boldsymbol{F}^*, \boldsymbol{RP}^*)), \forall i \in \boldsymbol{V} \\
s.t.\quad &U^*(\boldsymbol{F}, \boldsymbol{RP}) = \sum_{(\boldsymbol{f}_i, \boldsymbol{rp}_i) \in D} u_i(\boldsymbol{f}_i, \boldsymbol{rp}_i), \quad \boldsymbol{F}^* = \left(\boldsymbol{f}_1^*, \ldots \boldsymbol{f}_i^*, \ldots \boldsymbol{f}_m^*\right) \\
&\boldsymbol{RP} = \left(\boldsymbol{rp}_1\left(\boldsymbol{g}_1^*, \boldsymbol{c}_1^*\right), \ldots \boldsymbol{rp}_i\left(\boldsymbol{g}_i^*, \boldsymbol{c}_i\right), \ldots, \boldsymbol{rp}_m\left(\boldsymbol{g}_m^*, \boldsymbol{c}_m^*\right)\right) \\
&\boldsymbol{RP}^* = \left(\boldsymbol{rp}_1\left(\boldsymbol{g}_1^*, \boldsymbol{c}_1^*\right), \ldots \boldsymbol{rp}_i\left(\boldsymbol{g}_i^*, \boldsymbol{c}_i^*\right), \ldots \boldsymbol{rp}_m\left(\boldsymbol{g}_m^*, \boldsymbol{c}_m^*\right)\right).
\end{aligned}
\tag{12}
$$

As $u_i^*(\boldsymbol{f}_i, \boldsymbol{rp}_i)$ given in Eq. (5) is a strictly monotone decreasing function of $\boldsymbol{rp}_i$, we have

$$\forall i \in \boldsymbol{V}, \quad \boldsymbol{rp}\left(\boldsymbol{g}_i^*, \boldsymbol{c}_i\right) \leqslant \boldsymbol{rp}\left(\boldsymbol{g}_i^*, \boldsymbol{c}_i^*\right). \tag{13}$$

By substituting $\boldsymbol{rp}_i$'s definition into inequality (13), we can rewrite it into inequality (14) as follows:

$$\left(\boldsymbol{c}_i - \boldsymbol{c}_i^*\right) + \left(\boldsymbol{g}_i^* - \boldsymbol{g}_{i+1}^*\right)^T diag\left(\boldsymbol{c}_i - \boldsymbol{c}_i^*\right)\left(\boldsymbol{g}_i^* - \boldsymbol{g}_{i+1}^*\right) \leqslant 0. \tag{14}$$

As the inequality (14) sets up for all the $\boldsymbol{c}_i$ where $i \in \boldsymbol{V}$, we can obtain Eq. (15) by substituting $\boldsymbol{c}_i = 2\boldsymbol{c}_i^*$ and $\boldsymbol{c}_i = \boldsymbol{0}$ into inequality (14).

$$\boldsymbol{c}_i^* + \left(\boldsymbol{g}_i^* - \boldsymbol{g}_{i+1}^*\right)^T diag\left(\boldsymbol{c}_i^*\right)\left(\boldsymbol{g}_i^* - \boldsymbol{g}_{i+1}^*\right) = \boldsymbol{0}. \tag{15}$$

Taking into account Eq. (11), $\boldsymbol{rp}_i^*$ at the Nash equilibrium can be simplified into Eq. (16).

$$\boldsymbol{rp}_i^* = \left(\boldsymbol{c}_{i+2}^* - \boldsymbol{c}_{i+1}^*\right)(\boldsymbol{1})^T, \forall i \in \boldsymbol{V}. \tag{16}$$

Considering the definition of the Nash equilibrium again, we can have another inequality (17) as follows:

$$
\begin{aligned}
&\forall i \in \boldsymbol{V}, \quad U^*(\boldsymbol{F}', \boldsymbol{RP}') \leqslant U^*(\boldsymbol{F}^*, \boldsymbol{RP}^*)) \\
&s.t.\quad U^*(\boldsymbol{F}, \boldsymbol{RP}) = \sum_{(\boldsymbol{f}_i, \boldsymbol{rp}_i) \in D} u^*(\boldsymbol{f}_i, \boldsymbol{rp}_i), \\
&\boldsymbol{RP}' = \left(\boldsymbol{rp}_1\left(\boldsymbol{g}_1^*, \boldsymbol{c}_1^*\right), \ldots \boldsymbol{rp}_i(\boldsymbol{g}_i, \boldsymbol{c}_i), \ldots, \boldsymbol{rp}_m\left(\boldsymbol{g}_m^*, \boldsymbol{c}_m^*\right)\right) \\
&\boldsymbol{RP}^* = \left(\boldsymbol{rp}_1\left(\boldsymbol{g}_1^*, \boldsymbol{c}_1^*\right), \ldots \boldsymbol{rp}_i\left(\boldsymbol{g}_i^*, \boldsymbol{c}_i^*\right), \ldots \boldsymbol{rp}_m\left(\boldsymbol{g}_m^*, \boldsymbol{c}_m^*\right)\right) \\
&\boldsymbol{F}' = \left(\boldsymbol{f}_1^*, \ldots \boldsymbol{f}_i, \ldots \boldsymbol{f}_m^*\right), \boldsymbol{F}^* = \left(\boldsymbol{f}_1^*, \ldots \boldsymbol{f}_i^*, \ldots \boldsymbol{f}_m^*\right).
\end{aligned}
\tag{17}
$$

According to the RP's definition in Eq. (11) and the simplified format in Eq. (16), we can transform inequality (17) into inequality (18) by canceling the zero items and keeping the $(\boldsymbol{g}_i, \boldsymbol{c}_i)$—related items in the inequality.

$$
\begin{aligned}
u^*\Big(\boldsymbol{f}_i, &\left(\left(\boldsymbol{c}_i - \boldsymbol{c}_{i+1}^*\right) - \left(\boldsymbol{c}_{i+1}^* - \boldsymbol{c}_{i+2}^*\right)\right)(\boldsymbol{1})^T \\
&+ \left(\boldsymbol{g}_i - \boldsymbol{g}_{i+1}^*\right)^T diag(\boldsymbol{c}_i)\left(\boldsymbol{g}_i - \boldsymbol{g}_{i+1}^*\right) \\
&- \left(\boldsymbol{g}_{i+1}^* - \boldsymbol{g}_{i+2}^*\right)^T diag\left(\boldsymbol{c}_{i+1}^*\right)\left(\boldsymbol{g}_{i+1}^* - \boldsymbol{g}_{i+2}^*\right)\Big) \\
&\leqslant u^*\left(\boldsymbol{f}_i^*, \left(\boldsymbol{c}_{i+2}^* - \boldsymbol{c}_{i+1}^*\right)(\boldsymbol{1})^T\right).
\end{aligned}
\tag{18}
$$

Note that this inequality holds for all $i \in \boldsymbol{V}$, and we can obtain inequality (19) by setting $\boldsymbol{c}_i$=$\boldsymbol{0}$ in the inequality (18).

$$u^*\left(\boldsymbol{f}_i, \left(\boldsymbol{c}_{i+2}^* - \boldsymbol{c}_{i+1}^*\right)(\boldsymbol{1})^T\right) \leqslant u^*\left(\boldsymbol{f}_i^*, \left(\boldsymbol{c}_{i+2}^* - \boldsymbol{c}_{i+1}^*\right)(\boldsymbol{1})^T\right). \tag{19}$$

Without the loss of generality, inequality (19) can be reorganized into Eq. (20) based on the u_i's definition as follows:

$$\boldsymbol{f}_i^* = \arg\max_{\boldsymbol{f}_i \in \mathbb{F}} u_i\left(\boldsymbol{f}_i, \left(\boldsymbol{c}_{i+2}^* - \boldsymbol{c}_{i+1}^*\right)(\boldsymbol{1})^T\right) = \arg\max_{\boldsymbol{f}_i \in \mathbb{F}} \left(u_i^*(\boldsymbol{f}_i) + \left(\boldsymbol{c}_{i+2}^* - \boldsymbol{c}_{i+1}^*\right)(\boldsymbol{1})^T\right). \tag{20}$$

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As described in Eq. (20), we argue that $\boldsymbol{f}_i^*$ is the optimal solution in $u(\boldsymbol{f}_i, (\boldsymbol{c}_{i+1}^* - \boldsymbol{c}_{i+2}^*)$'s feasible solution space, where u_i^* reaches the maximum value for all $i \in \boldsymbol{V}$. Hence, the Karush–Kuhn–Tucker (KKT) condition is satisfied, which can be characterized as $\nabla u_i^* \left(\boldsymbol{f}_i^*\right) + \mu_i + \nu_i = 0, \forall i \in \boldsymbol{V}$.

By summing all the KKT conditions for each $i \in \boldsymbol{V}$, we have a new KKT condition as Eq. (21).

$$\sum \nabla u_i^* \left(\boldsymbol{f}_i^*\right) + \sum \mu_i + \sum \nu_i = \sum \left(\nabla u_i^* \left(\boldsymbol{f}_i^*\right) + \mu_i + \nu_i\right) = 0. \tag{21}$$

As the KKT condition is sufficient and necessary, the Nash equilibrium $\boldsymbol{F}^* = \left(\boldsymbol{f}_1^*, \dots \boldsymbol{f}_i^*, \dots \boldsymbol{f}_m^*\right)$ is proved to be the optimal solution to the global optimal problem in Eq.(22).

$$\begin{aligned} \boldsymbol{F}^* &= \arg \max_{\boldsymbol{f}_i \in \mathbb{F}} \sum_{i \in V} \left(u_i^*(\boldsymbol{f}_i) + \left(\boldsymbol{c}_{i+2}^* - \boldsymbol{c}_{i+1}^*\right) (\mathbf{1})^T\right) \\ &= \arg \max_{\boldsymbol{f}_i \in \mathbb{F}} \sum_{i \in V} u_i^* \left(\boldsymbol{f}_i, \left(\boldsymbol{c}_{i+2}^* - \boldsymbol{c}_{i+1}^*\right) (\mathbf{1})^T\right) \\ &= \arg \max_{\boldsymbol{f}_i \in \mathbb{F}} \sum_{i \in V} (u_i(\boldsymbol{f}_i)) = \arg\max U(\boldsymbol{F}). \end{aligned} \tag{22}$$

□

6. PERFORMANCE EVALUATION

6.1. Simulation setup

We evaluate the performance of the cooperative offloading on data recovery in MATLAB by using the data traces generated from GEMV^2 [35], which is a geometry-based, efficient propagation model for V2V and vehicle–infrastructure communications. Different from the simple statistical propagation models that do not account for surrounding objects explicitly, GEMV^2 uses the outlines of vehicles, buildings, and foliage to distinguish all the channel links (line of sight and non-line of sight due to signal blocks in the traffic). For each link, GEMV^2 calculates both large-scale signal variations and small-scale signal variations that scale well by simulating radio propagation even for city-wide networks. According to [35, 36], the data traces are generated in the following several steps:

(1) *Vector map interception:* Intercept a vector map from the open street map that contains the whole traffic information of the trajectory, such as the road network, the traffic lights, overtaking rules, and speed limitations.
(2) *Block abstraction:* Abstract the information on all the blocks from the vector map, such as buildings, trees, and vehicle bodies, and import it to the GEMV^2. All these signal blocks are described as polyhedrons in the propagation model.
(3) *GEMV^2 configuration:* Set the parameters of vehicles, such as the number of vehicles, speed, and acceleration in GEMV^2. Run the simulations, and generate the trace files that contain the information on channel statues, including GPS location, vehicle speed, and timestamps.

To make fair comparisons, we use the same configuration in the simulation to compare the performance of our scheme and other broadcast schemes. As shown in Figure 5, a vector map with the area of 51.5094N 51.5184N, −0.1025W −0.0776W in London is intercepted from open street map, and all the vehicles are driving in the area to acquire the traffic information such as channel links, vehicle speed, GPS position, and others. The reason why we choose such an area is that the trajectories in this vector map contain many blocks on the road such as buildings and trees, which can cause frequent data loss in the broadcast and allow a full test of different reliable broadcast schemes. The vehicle speed is set to 100 km/h, and the average acceleration is 3 m/s^2. The duration of each time slot is 2 ms in the STDMA, and the TTL for each CAM is set to 100 ms.

The length of time slot is the same as that in [10], in which all communications were conducted using broadcast at 2 Mbps and each vehicle broadcasts routine messages every 2 s. This configuration is also feasible in the simulations. Considering the data payload is 53 bytes, whereas other

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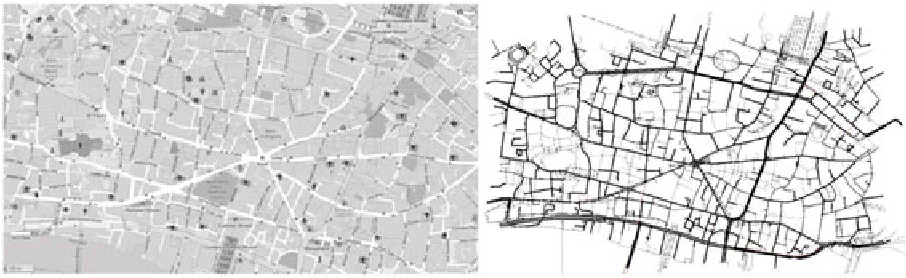

Figure 5. Open street map and vector network in London.

authentication takes up 209 bytes, each slot can hold one routine message together with 74 piggybacked messages, that is, $209 + 53 + 53 \times 74 < 2 \times 10 - 3 \times 2 \times 1024 \times 1024$, which is sufficient for the cooperative piggybacking in the VANET.

Another two existing broadcast schemes are selected for reference and comparison with our cooperative offloading scheme:

(1) *TDMA-based flooding* [24]: There are two separated processes in the TDMA-based flooding: (1) Any vehicle with CAM loss should send out a request that contains the lost information based on TDMA. (2) All the vehicles that have received this request should retransmit the requested CAM if it has been received successfully. To reduce the propagation latency in the broadcast, the number of slots for the CAM flooding (the second process) is limited; that is, around 50% of the slots in one frame is used for CAM flooding.
(2) *Geo-based forwarding* [27]: Any vehicle with CAM loss should broadcast a request for retransmission, and all the other vehicles would calculate an optimal forwarding point based on the geometric position of the vehicle that has generated the request and all the other vehicles' position. The vehicle that is nearest to the ideal forward point will be selected as the optimal forwarder and retransmit the requested CAMs.

We use the following performance metrics for comparison:

(1) *Average reliability*: For each CAM broadcast in the cooperative offloading, its reliability is defined as the ratio of the number of vehicles that have received this CAM before its TTL expires to the total number of vehicles that are interested in this CAM. Then, the average reliability is defined as the average value of all the CAM's reliabilities during the time of interest.
(2) *Convergence speed*: The converge speed describes the time spent by the cooperative offloading game on converging to the optimal solution.

6.2. Simulation results

Figure 6 gives an overview of the average reliability by varying the number of vehicles from 4 to 16. It can be seen that cooperative offloading can achieve a much higher broadcast reliability (most above 95%) than TDMA-based flooding and geo-based forwarding. The reason is that the vehicles in the cooperative offloading can obtain more information on the network topology via learning from other vehicles piggybacking, which can lead to a better piggybacking decision comparing with other related schemes.

Besides, the average reliabilities in TDMA-based flooding and geo-based forwarding decrease significantly against the increase of the number of vehicle as each vehicle has less slots to broadcast before the TTL when the number of vehicles increases in the cooperative offloading. However, the vehicles in the cooperative offloading can learn from other vehicles piggybacking quickly and converge to the optimal decision in a limited number of iterations (Table I), which is hardly impacted by the increase of the number of vehicles.

Figure 7 shows the cumulative distribution function of the time interval of two adjacent received CAMs in different broadcast schemes where the number of vehicles is set to 4.

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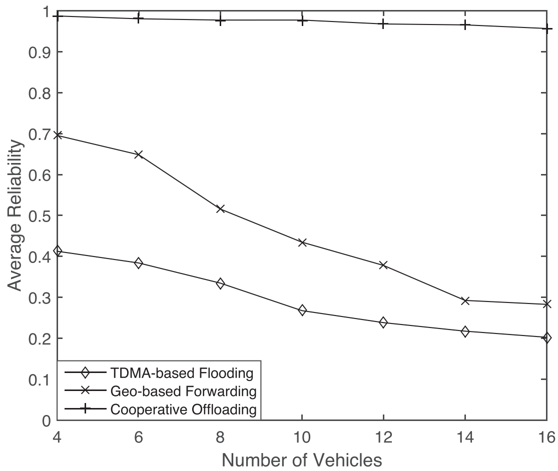

Figure 6. Broadcast reliability against different vehicle numbers. TDMA, time division multiple access.

Table I. Converge Speed in CAM Offloading.

Vehicle numbers	Average iteration rounds	Average convergence time (ms)
4	9.4	18.8
6	10.1	20.2
8	13.4	26.8
10	16.5	33.0
12	20.7	41.4
14	27.6	55.2
16	35.9	71.8

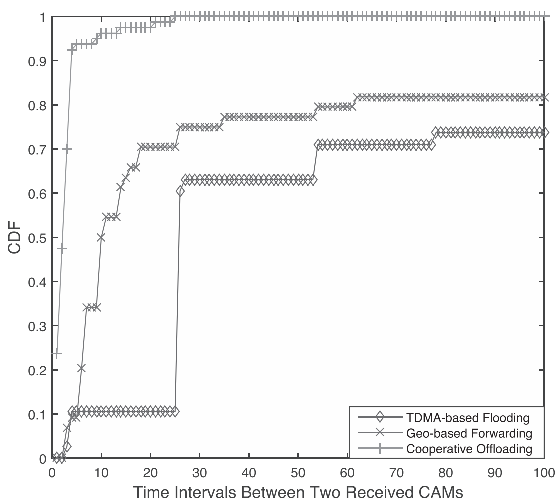

Figure 7. Cumulative distribution function (CDF) of time intervals between two received cooperative awareness messages (CAMs). TDMA, time division multiple access.

Followed by the geo-based forwarding, the proposed cooperative offloading scheme achieves the highest reliability. More than 90% of any two adjacent CAMs can be received reliably in 8 ms, and all packets are reliably received within 25 ms.

The TDMA-based flooding has the lowest reliability. The reason can be explained as follows: After each vehicle's broadcast, there is a fixed time duration (50% of the slots in one frame) that is used to implement the CAM flooding. Any vehicles with lost CAMs will broadcast a request,

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and other vehicles that have overheard the request will retransmit the corresponding CAM if it has received the lost CAM. The problem is that there exist too many copies of the requested CAM in the VANET that can result in frequent data collisions in the flooding duration, not to mention the huge communication overhead that can cause a heavy overload in the VANET.

Comparing with the TDMA-based flooding, the geo-based forwarding can recover more CAMs and achieve a higher reliability. As the forwarder that retransmits the requested CAM is carefully calculated and selected based on the geometric information, it has a high possibility that the forwarder can overpass the blocks between the source vehicle and the vehicle that requests the CAM. However, the geometric position is not the only fact that leads to the CAM loss in the broadcast. For example, the height of the antenna's position and power can also have a significant influence on channel link quality. This also explains why the forwarder-based broadcast still cannot achieve a high reliability as that in the cooperative offloading scheme.

Figure 8 shows the reward–penalties of the four vehicles for eight iteration rounds in the cooperative offloading game. The reward–penalty is calculated according to the deviations between each vehicle's proposal and that of its neighbors. The larger the deviation is, the more penalties and less rewards it will receive in the broadcast. It can be seen that all vehicles in the cooperative offloading game can learn more information mutually from the suggestions and corresponding credits in the received proposals from other vehicles' broadcast, which helps all vehicles make more efficient decisions on cooperative data offloading and converge to a global optimal solution. Finally, all the vehicles' decisions on the data offloading converge to the optimal solution at the eighth iteration, where the RPA in each vehicle is 0.

Table I shows the convergence speed in the cooperative offloading game regrading to the number of iteration rounds and the convergence time. The iteration rounds and the convergence time increase

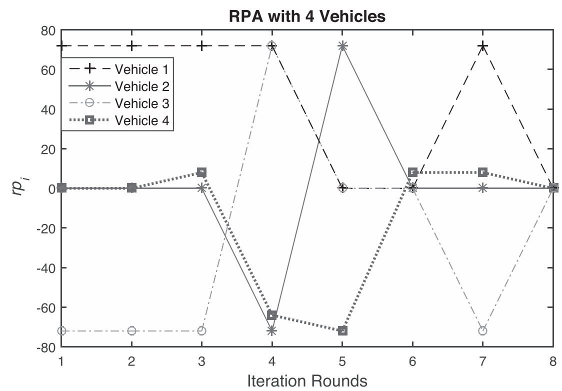

Figure 8. Reward–penalties in a four-vehicle offloading game. RPA, reward–penalty algorithm.

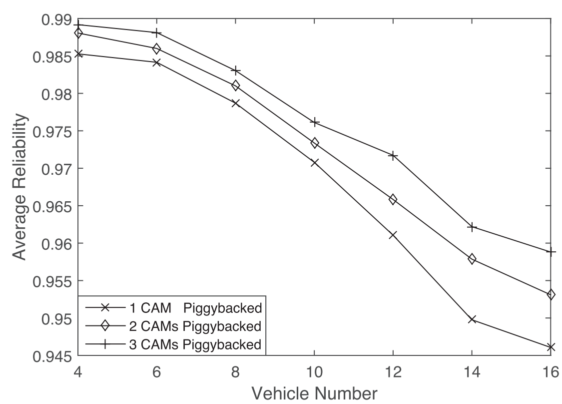

Figure 9. Different number of piggybacked cooperative awareness messages (CAMs) in the cooperative offloading.

gradually when the vehicles' number increases. As the duration in each time slot in STDMA is fixed (2 ms), the more vehicles there are in the VANET, the less time slots each vehicle can have before its CAM's TTL. Hence, the convergence speed will decrease with the increase of vehicle number.

Figure 9 shows the average reliability with different number of piggybacked CAMs. The larger the w is, the higher reliability the cooperative broadcast will achieve, as the lost CAMs can be recovered with a higher probability when more CAMs are piggybacked. In fact, the proposed scheme can achieve a high broadcast reliability even when only one CAM is piggybacked, that is, $w = 1$. Increasing the number of piggybacked CAMs can increase both the broadcast reliability and the convergence speed, but it can also result in overload and unbalance in the VANET, which is similar to the flooding-based retransmission scheme.

7. CONCLUSION

To achieve the accident-free driving, we proposed a cooperative offloading game to solve the reliable broadcast problem in VANET, in which the V2V communications are employed to virtually broaden the driving visibility and improve the safety when driving on the road.

Each vehicle in the VANET is allowed to broadcast routine CAMs periodically and piggyback some received CAMs cooperatively to offload the task of data recovery in the VANET. To make an optimal cooperation in data recovery, a reward–penalty scheme is adopted in the data offloading process to supervise all the piggyback decisions converged to the Nash equilibrium, which is also proved to be the global optimal solution to the problem of reliable broadcast; otherwise, the vehicles can be trapped in the local optimal with turbulences because of the unreliable channel links and the incomplete local information in the decentralized piggyback. Simulation results demonstrate that the proposed cooperative offloading scheme can achieve a much higher broadcast reliability compared with other existing solutions, which can be easily extended to other applications, such as the smart driving and automatic vehicles.

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