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Cooperative Data Delivery in VANETs based on Evolutionary Fuzzy Game

Jianhua Liu[a,b,*], Xin Wang[c], Guangxue Yue[a], Shigen Shen[d,a]

[a]College of Mathematics, Physics and Information Engineering, Jiaxing University, Jiaxing 314001, China
[b]Department of Computer Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[c]Department of Electrical and Computer Engineering, State University of New York at Stony Brook, Stony Brook, NY 11790
[d]Department of Computer Science and Engineering, Shaoxing University, Shaoxing 312000, China

Abstract

This paper proposes a novel approach making use of evolutionary fuzzy game theory to find the optimal cooperative strategies with the goal to improve reliable data delivery in vehicle-to-vehicle communications. The encounter nodes form a contact graph based on a inter-contact time to efficiently deliver stored data each other. We propose a real-time cache updating algorithm to optimize the cost of caching and distributing data over a wireless link by updating the factor of data distribution and cache queue. The algorithm of real-time cooperative data delivery is formulated to determine the tradeoff between maximizing the data delivery rate and minimizing the time delay using accuracy and adaptability of the optimization strategy between requester nodes and responder nodes. The solutions obtained by the new algorithms are compared with non-cooperative data delivery without contact times. The results show that the proposed algorithm in data delivery delay and throughput outperforms non-cooperative data delivery by 1%, 33%, respectively.

Keywords: Cooperative communications, Data delivery, Game theory, Vehicular networks

1. Introduction

Vehicular ad hoc networks (VANETs) consist of vehicles that can communicate with each other opportunistically, and are expected to support various information services in the near future [1]. However, because of the unpredictable node movement and the resulted dynamics in wireless links, VANETs suffer from disrupted connections and limited contact opportunities. This can lead to a long delay in data delivery, which cannot meet the requirements of emergent applications such as those for surveillance [2]. To ensure the quality of experience for the users, it is of critical importance to ensure more reliable data delivery among vehicles.

As vehicles are exploited to carry and forward data, the bandwidth and caching space are shared resources[3]. To improve the success rate of data delivery, it is crucial to determine the appropriate data delivery strategy for data transmissions. In existing work, vehicles tend to forward packets to nearby nodes without considering their conditions. In vehicle-to-vehicle (V2V) communications, connections among nodes are intermittent due to the movement of

*Corresponding author. Tel.: +86 13758397927.
Email addresses: ljh_541@163.com (Jianhua Liu), xwang@ece.sunysb.edu (Xin Wang), guangxueyue@163.com (Guangxue Yue), shigens@126.com (Shigen Shen)

vehicles and the resulted link breakage. If data are forwarded to a node with broken links without transmission options, it will result in higher delivery delay and even packet dropping. Therefore, there is a need for the group of vehicle nodes in a neighborhood to determine their individual data delivery strategies and be cooperative in transmissions.

Although efforts have been made to increase the chance of successful data delivery in VANETs [4, 5], there is very limited research on the scheduling of cache usage for vehicles, as it is difficult to design a reliable delivery strategy to minimize the transmission delay with constant disconnections and limited effective bandwidth [6]. In this paper, we investigate a set of schemes to ensure vehicles to more reliably deliver data at any time. We will construct a contact graph to capture the contact vehicles, and exploit cooperative caching to accelerate the data forwarding and reduce the transmission delay in the V2V communications.

Cooperative caching has been applied in wireless ad hoc networks [7] and peer-to-peer (P2P) networks [8, 9] to allow nodes to share the cache space, and a Femto-Caching scheme was proposed in [10] for wireless systems. These schemes, however, cannot be applied in VANETs. The high vehicle mobility and varying node distances make it difficult to estimate the cache usage and data transmission delay, which prevents the design of an efficient cache management strategy to reduce the cache overflow and the amount of obsolete data. In addition, to increase the chance of data access in the presence of intermittent connections in the V2V communications, a data block may need to be cached at different vehicle nodes, while this is not necessary for a general network.

Besides mobility and resource limitation, vehicle nodes tend to be selfish and can decide whether to be cooperative in the network. The non-cooperation may result in congestion and inefficient resource usage, and even transmission failure. There is a need to create incentives for vehicles to be more cooperative in improving the efficiency of data delivery. In [12], authors proposed a nice incentive scheme based on coalitional game theory to solve the forwarding cooperation problem in VANETs. Recently, there has been a growing interest in modeling and analyzing communication systems using evolutionary game theory. Evolutionary game theory (EGT) [11] postulates that each player in a population periodically checks the alternative strategies to select the best one. Rather than only providing incentive to stimulate message forwarding in VANETs, where coalitional game is a good option, we will exploit EGT to determine appropriate cooperative data delivery strategies for data transmissions. Although Nash equilibria are widely used for the strategic optimization of evolutionary games, the global optima of specific cost functions cannot be determined under certain conditions. On the other hand, fuzzy set theory can well deal with incomplete information in the V2V communications.

In light of the problems faced by VANETs, we propose to introduce a finite evolutionary game with fuzzy payoffs [13], called evolutionary fuzzy game theory (EFGT). In our scheme, vehicle nodes can make subjective judgments based on their learning experiences with the incomplete information considered as fuzzy variables. To facilitate the use of cooperative caching for data delivery, each node periodically estimates its payoff based on the bandwidth and cache space of its neighborhood and selects the best strategy in each period. Because the caching space of a node is limited, we ensure that the data to store do not exceed the cache limits of vehicle nodes and the cache queue is dynamically updated based on the strategic decision of the evolutionary fuzzy game. Our performance results show that the proposed scheme can provide a high probability and low latency data delivery. *Our contributions of this paper can be summarized as follows:*

(1) We construct a contact graph based on the contact rate using dynamic programming. Nodes determine their waiting time and delivery action cooperatively.

(2) We propose a cooperative data delivery decision based on fuzzy payoff. Nodes cooperatively deliver data based on the information of their own cache space and the network bandwidth. Our approach is inspired by the evolutionary fuzzy game theory, following which the nodes dynamically adapt their data delivery strategies based on distributed information obtained upon encountering other nodes.

(3) We propose a cooperative data delivery scheme to determine the distribution actions in the contact graph G based on the payoff. The expected payoffs of the bandwidth and cache are dynamically adjusted, and the distribution factor for requester/responder nodes is modified based on the replicator dynamics. Our scheme considers the tradeoff between data accessibility and caching overhead while minimizing the average data delivery delay in the V2V communications. We analyze the theoretical characteristics of the scheme in terms of the expected fuzzy payoff and the stability of the game utility.

The remainder of this paper is organized as follows. Section 2 reviews some related work. Section 3 provides an overview of the system model, and then Section 4 describes our proposed game model for cooperative data delivery and its theoretical characteristics. Section 5 analyzes the Nash equilibrium conditions of the game payoff for contact nodes. Section 6 describes the details of our real-time cooperative data delivery scheme. The simulation setup and results of performance evaluations are presented in Section 7. Finally, in Section 8, we conclude this paper.

2. Related works

It is critical to support reliable data delivery in VANET to reduce the overall packet transmission time while ensuring a higher delivery rate with the cooperation of vehicle nodes. This issue has emerged as a promising area of research in the field of road networks [14–16]. There is a rich body of literature on several aspects of reliable data delivery, including reliable multicast in wireless mesh networks (WMNs), position-based opportunistic routing mechanisms in mobile ad hoc networks (MANETs), reactive routing enhancement in wireless sensor networks (WSNs), and vehicle-assisted reliable data delivery in VANETs. In [17], a high-throughput and reliable multicast protocol for WMNs was proposed. It seamlessly integrates four building blocks (tree-based opportunistic routing, intraflow network coding, source rate limiting, and round-robin batching) to support high-throughput, reliable multicast routing in WMNs. In [18], a reliable, energy-efficient multicast protocol with high throughput and fairness was designed for lossy wireless networks. This not only eliminates the need for coordination between nodes, but also improves the multicast throughput significantly by exploiting both intra-batch and inter-batch coding opportunities. A position-based opportunistic routing protocol was proposed in [19]to address the problem of delivering data packets in highly dynamic MANETs. In [20], a reliable transport mechanism that relies on acknowledgements (ACKs) and coding at the source was designed for DTNs with the aim of minimizing the round-trip file delay for a unicast session. The multi-period spraying of a single-packet file was considered to save as much energy as possible for unicast communication in a heterogeneous mobility DTN [21]. Providing reliable and efficient communication in industrial WSNs with dynamic and harsh environments is a major technical challenge, and a reliable reactive routing enhancement (R3E) has been presented to provide reliable and energy-efficient packet delivery over unreliable wireless links by utilizing the local path diversity [22]. Different from existing carry and forward solutions, the vehicle-assisted data delivery (VADD) protocol was proposed to forward packets to the best road with the lowest data-delivery delay by making use of predictable vehicle mobility [14]. In [15], an efficient safety data dissemination protocol was designed by exploring the feasibility and benefits of incorporating the data preferences of vehicles. In [23], a trajectory-based statistical forwarding scheme was proposed for infrastructure-to-vehicle data delivery. This data delivery is performed by computing a target point based on the current location and final destination of vehicles.

To combat unreliable data delivery for V2V communications, various cooperative data delivery technologies have been studied, including cache placement, rule caching [24], and improving the cooperation of nodes in wireless networks. In [24], cache rules are applied to significantly reduce the total cost of remote controller processing and ternary content addressable memory occupation. The algorithm proposed takes a greedy strategy and is run offline, with the condition that the network traffic is known in advance. The cache placement scheme in [25] is designed for a cooperative cache built from individual client caches in an online social network, where the algorithm leverages the relationship between clients and workload statistics. Caching popular multimedia content is a promising way of improving the potential performance of wireless networks. In [26], to evaluate the performance of the wireless HetNet and intelligently utilize the service characteristic such as the traffic redundancy, the authors propose to cache the most popular multimedia content via off-peak broadcasting taking into account the limited caching ability of both relays and users. Most cache placement algorithms use hop counts to measure the total cost of a caching system, but the hop delay in wireless networks varies. Two heuristic cache placement algorithms for wireless multi-hop ad hoc networks were presented in [27], where the benefit of selecting a particular cache node is determined based on the variations in contention and traffic flows. To minimize the content access delay for mobile users, a novel cooperative caching scheme is proposed for content-oriented networking based on Lagrangian relaxation [28]. Both centralized and distributed caching policies for minimizing the data access delay were studied in [29–32]. In [29], a novel centralized approach was designed to support cooperative caching in DTNs, which enables the sharing and coordination of cached data among nodes to reduce the data access delay. The storage capacity of mobile devices is typically limited. In [31], a fully distributed mechanism for determining the caching policy of each mobile user was presented. This is designed for a heterogeneous environment in which the demand for content, access to resources, and mobility characteristics vary across different users. By taking an evolutionary theory-based approach, [32] developed a distributed information-based cooperation ushering scheme to promote cooperation in message forwarding between nodes.

Game-theoretic approaches have also been used to study adaptive caching [33] and data delivery [12, 34] problems. In [33], the estimated request probabilities were used to formulate the adaptive caching problem as a non-cooperative repeated game, and an adaptive popularity-based video caching algorithm was proposed by considering slow and fast timescales. This algorithm permits the servers to coordinate their caching strategies in a distributed fashion. In [12], an incentive scheme was used to stimulate message forwarding in VANETs based on coalitional game theory. In [34], the problem of cooperative packet delivery to mobile nodes in a hybrid wireless mobile network was considered and the behavior of rational mobile nodes was analyzed in regard to cooperative packet delivery using a coalitional game. Eventually, a distributed algorithm was found to obtain the stable coalitions.

This paper is inspired by the related studies described above, particularly [13, 29, 32–34]. In [13], considering a finite extensive game with fuzzy payoffs, the new concept of credibilistic equilibria is similar to the Nash equilibrium in a deterministic environment, whereas our work uses a fuzzy payoff inference system to adaptively change the optimal strategy and extend EFGT to improve the accuracy and adaptability of the optimal strategy. In [29], the basic idea was to intentionally cache data at a set of central network locations and coordinate the usage of cached data among multiple nodes to reduce the data access delay. In comparison, our work focuses on real-time and distributed scheduling of data delivery actions in the V2V communications on the contact graph. The scheme in [32] follows the evolutionary game theory, where nodes dynamically adapt their message forwarding strategies through self-evaluation based on their own and network performance. In contrast, our work considers real-time cooperative data delivery in the contact graph, and uses data distribution or cache strategy to deliver data. The expected payoffs of players are evaluated in terms of bandwidth and cache space based on a fuzzy inference system prior to the cooperative decision of data delivery actions. Considering the storage and latency costs associated with accessing remote replicas of the requested videos, server caching decisions were formulated as a non-cooperative game in [33], whereas our method formulate the problem of decision of data delivery actions between contact vehicle nodes as a cooperative evolutionary game. In [34], the payoff of each mobile node was determined using a Markov chain model, and the expected cost and packet delivery delay are obtained when the mobile node is in a coalition. In this paper, we instead use EFGT to analyze cooperative data delivery strategies selected by encounter vehicle nodes according to the payoff of bandwidth and cache space.

3. System model

In this paper, we propose to apply a game theoretic cooperative data delivery technique to counter disrupted connections in V2V communications for more reliable and timely data delivery. In this section, we introduce our basic data forwarding model and the problem to study.

3.1. Data forwarding model for V2V communications

Before presenting our scheme, we would like to show how our system could function with an example on map sharing between vehicles. Each vehicle can download map around a local area using the cellular network. To reduce the wireless transmission cost and charge, vehicles may choose to share the map data downloaded individually when they encounter on the road. An example scenario is shown in Fig.1. Nodes $v1$, $v2$, $v3$ and $v4$ are within the communication range and form a contact graph. Suppose node $v1$ is moving towards the right and using the map downloaded to navigate a geographic region. Node $v2$ is moving towards the left and using the map it downloaded. Similarly, nodes 3 and 4 also carry their own regional maps. Although nodes $v1$ and $v2$ would like to share their cached map data with each other, the link between nodes $v1$ and $v2$ is disrupted and has low bandwidth, so nodes $v1$ and $v2$ will choose to cache the map data instead. Vehicles continue to move forward. In Fig.2, when the cache space and bandwidth between nodes $v2$ and $v4$ are high or medium, $v2$ and $v4$ will take the distribution action. Now the link between $v1$ and $V3$ has enough bandwidth but the cache space of node $v3$ is low and cannot hold additional data. Although the node $v3$ can choose to distribute data to the node $v1$, the node $v1$ cannot distribute data to node $v3$ but has to take the cache action.

Let us consider V2V communications among N vehicle nodes on the road. The opportunistic contacts between vehicles are described by a contact graph $G(V, E, W)$, where the stochastic contact process between a vehicle pair $i, j \in V$ is modeled as an edge $e_{ij} \in E$ in the graph. Two vehicles can communicate when their distance is smaller than the communication range. When a vehicle i has a contact with the vehicle j, they can decide if they will distribute

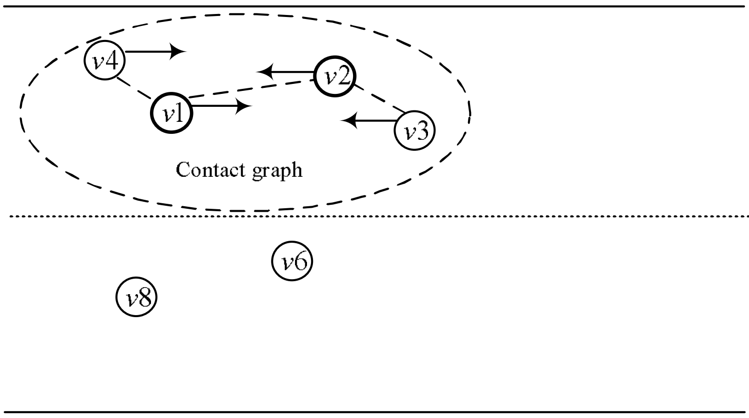

Figure 1. The cooperative delivery in the V2V communications.

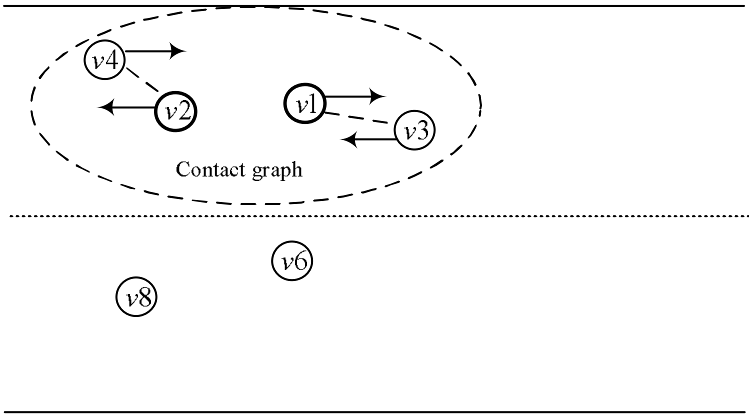

Figure 2. The cooperative delivery in the V2V communications.

the cached data to each other through their wireless links e_{ij} or e_{ji}. The data sharing process can be initiated by a requester, and the node being contacted is a responder. The time required to distribute cached data over a wireless link edge $e_{ij} \in E$ is determined by the inter-contact time and the bandwidth of the link between vehicles i and j. The pairwise inter-contact time follows an exponential distribution [36]. Let the contact time τ_s between the contact nodes follow an exponential distribution with contact rate λ_s. The weight W of the link edge between the requester node i and the responder node j in the inter-contact time T can be written as:

$$W = \int_0^T p_{\tau_s}(z)dz = 1 - e^{-\lambda_s T}, \tag{1}$$

where $p_{\tau_s}(z) = \lambda_s e^{-\lambda_s z}$ is the probability density function (PDF) .

3.2. Online cooperative data delivery

Consider a node with the cache space of B_s blocks. If the data block requested by a vehicle node is not in its own cache, it will request the block from a set of nodes in contact. The block can be obtained from another node only if there exists a contact edge between the requester and the node which has the data block cached, and the contact edge will remain during the cooperative data delivery period. Although the distribution of cached data blocks involves the storage cost and requires bandwidth to transmit, the data sharing helps contact nodes to quickly obtain the data of interests. Compared to the high cost in transmitting data through the cellular links, this local cost would be smaller.

The cooperative transmissions will help further trade off among bandwidth and cache space to provide faster delivery of data blocks among nodes with opportunistic contacts.

For two vehicle nodes in contact, let v_a and v_p denote the requester and the responder which involve in the data delivery at time $t(t < T)$. Let m_a and m_p denote the number of data blocks to share by v_a and v_p, respectively. To maximize the delivery rate and retain a finite average queue length in the cache, an adaptive cooperative data delivery is needed to determine the action to take by each sharing node.

The distribution and cache actions to take by a vertex in the contact graph G are represented by a pair $< e, c >$. When $(v_a, v_p) \in E$, the action o_a taken by the node v_a is relative to the action o_p taken by its contact node v_p. Similarly, when $(v_p, v_a) \in E$, the action o_p taken by the node v_p is relative to the action o_a taken by its contact node v_a. Let $\chi_{e,c}$ be the probability of a successful distribution of the cached data blocks, r_e is the delivery rate. The optimal action taken by the node based on bandwidth and cache conditions in the contact graph G is $o^* \in \arg\max_{e,c} r_e \chi_{e,c}$.

Our goal is to maximize the number of data blocks that can be successfully delivered over a finite contact time T. We will design a strategy based on the theory of evolutionary fuzzy game to facilitate contact nodes to take a cooperative data delivery action. This can be formulated as an online cooperative data delivery optimization problem (OCDOP). During the contact time T, contact nodes will cooperatively determine the delivery strategies to maximize the number of data blocks to exchange between them. Consider a cooperative data delivery scheme π that selects a (distribution, cache) action pair $< e^\pi(t), c^\pi(t) >$ for the data block delivery at time t. The action selected under π depends on the inference of the bandwidth condition, which could be high, medium, or low. Let the random variable $s^\pi_{e,c}(T)$ denote the number of distribution attempts (i.e., the number of data blocks sent) under an action $< e^\pi(t), c^\pi(t) >$, then the total amount of time taken to transmit the data under all the strategies by the contact nodes should not exceed the time duration T:

$$\sum_{e,c} s^\pi_{e,c}(T)\frac{B_e}{r_e} \leq T \, , \tag{2}$$

where B_e is the size of each block.

Data can be delivered when the bandwidth has medium or high rate, but not if the rate is too low.Let a binary random variable $Z_{e,c}(i)$ represent the high and medium ($Z_{e,c}(i) = 1$) or low ($Z_{e,c}(i) = 0$) of the bandwidth between contact nodes, we assume that $Z_{e,c}(i), i = 1, 2, ...,$ are independent and identically distributed. Wald's lemma implies that the expected number of successfully sent cache data blocks up to time T is $E\left[\sum_{e,c}\sum_{i=1}^{s^\pi_{e,c}(T)} Z_{e,c}(i)\right] = \sum_{e,c} E\left[s^\pi_{e,c}(T)\right]\chi_{e,c}$. Thus, our objective is to maximize the expected number of successfully sent cache data blocks:

$$\begin{aligned} \max_{\pi} \quad & \textstyle\sum_{e,c} \mathrm{E}\left[s^\pi_{e,c}(T)\right]\chi_{e,c}, \\ s.t. & \sum_{e,c} s^\pi_{e,c}(T)\tfrac{B_e}{r_e} \leq T \, . \end{aligned} \tag{3}$$

In the above optimization problem, a distribution or cache action is selected.

4. Cooperative data delivery game for the V2V communications

In this section, we first formulate a game model for the cooperative data delivery for the V2V communications. We then deduce the Nash equilibrium condition for such a system to maximize the number of cached data blocks successfully sent. Finally, we demonstrate that the cooperative data delivery game converges to the stable state.

4.1. Cooperative data delivery based on evolutionary fuzzy game

We now propose a cooperative data delivery algorithm based on an evolutionary fuzzy game that can be operated in a distributed cooperative manner in the vehicle network for more reliable and timely data delivery. To find the optimal strategy for cooperative data delivery during the contact time T, we use a fuzzy payoff inference system to adaptively change the cooperative strategy. As the operation is cooperative, even if a single node selects its optimal strategy and gains a payoff, the system continues to evolve until the game payoff and the payoff converge together.

The cooperative data delivery strategy based on an evolutionary fuzzy game is illustrated in Fig.3. To find a local cooperative data delivery strategy in an efficient manner, we divide OCDOP into two phases: fuzzy payoff inference and minimum-cost cooperative data delivery. In the fuzzy payoff inference phase, the requester and responder determine which cooperative data delivery strategy to employ through the fuzzy payoff inference. In the next phase, nodes in the contact range obtain the updated cache queue and contact list, and selects a strategy to minimize the cost of cooperative data delivery while guaranteeing reliable data delivery in the V2V connection. The second phase is carried out iteratively until the data delivery converges in contact graph G. In this stage, we prove the evolutionary stability of the fuzzy payoff by solving a replicator equation.

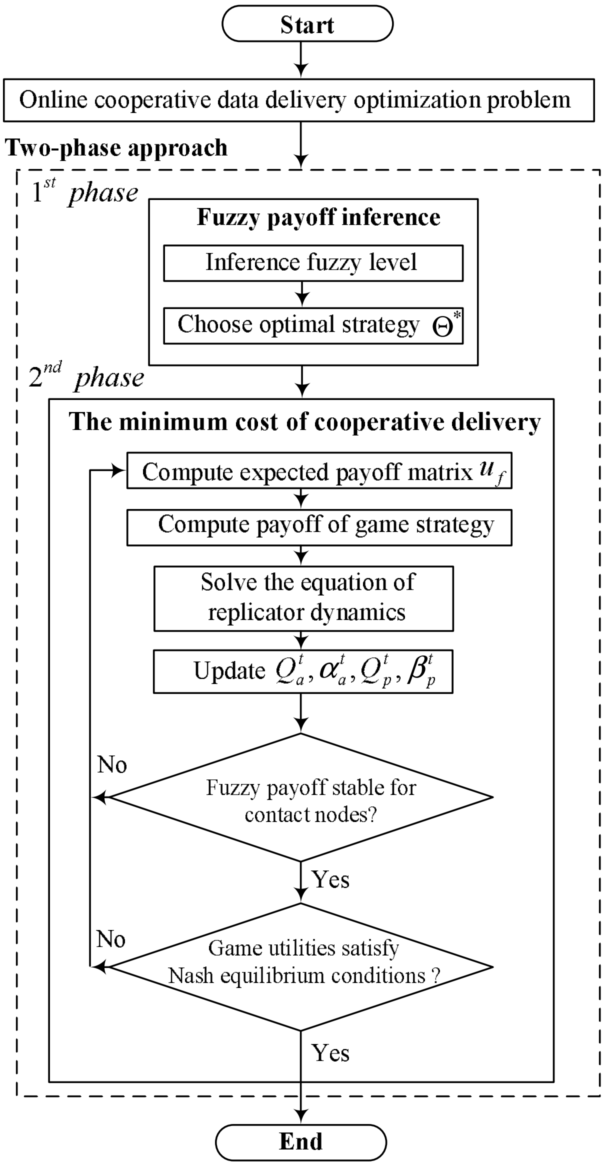

Figure 3. Flow chart for cooperative data delivery based on evolutionary fuzzy game.

Before presenting the detailed design of our game framework, we provide a definition.

Definition 1 A finite extensive evolutionary fuzzy game is defined as a tuple

$$\Omega = (N, Fr, Pr, O, \Theta, \succ_i, U), \tag{4}$$

which consists of the following components:

N is a set of rational nodes which act as players in the game and denoted by $N = \{v_a, v_p\}$.

Fr is a pair of fuzzy variables representing respectively the payoffs of bandwidth and cache space, $Fr = \{b, h\}$.

Pr is a function of the fuzzy membership. It describes the fuzzy variables b and h using values in the fuzzy sets. It can infer the fuzzy level of bandwidth and cache space, and the inference results on bandwidth and cache space include *low*, *medium* and *high*.

O is a set of actions available to the players, where $O = \{o_a, o_p\}$. An action of node V_x is represented as $o_x = \{e, c\}$, where e denotes the action to take for the data distribution over an edge, and c denotes the action to take for caching data block.

Θ is the set of strategies players could take during the contact time T. For distributing data blocks between two contact nodes v_a and v_p, there are four strategies the two nodes could cooperatively take, with $\Theta = o_a \times o_p = \{ee, ec, ce, cc\}$.

$\succ_i$ is a dominant equilibrium preference relation for each player $v_i \in N$.

U is the payoff of the game player and represented as $U(v_i, \Theta_i)$, where v_i is a player in the contact graph G. The expected fuzzy payoff $u_f(v_i, \Theta_i)$ denotes the benefits gained through the cooperative data delivery using the bandwidth of links between contact nodes and their cache space.

When two vehicle nodes encounter on the road, there are four possible strategies the two nodes could cooperatively take:

1. When the fuzzy payoffs of the transmission bandwidth and cache space are medium or high at time t, contact nodes v_a and v_p take the distribution strategy $\Theta_1 = \{ee\}$ to gain the desired data blocks, and the distribution action Θ_1 is an optimal strategy to take by both nodes v_a and v_p.
2. When node v_a meets node v_p, if the fuzzy payoffs of the transmission bandwidth of node v_a and v_p are medium or high at time t, and the fuzzy payoff of the cache space of node v_a is low at time t, the requester node v_a will choose to distribute data to the node v_p, while the responder node v_p will choose to cache the data rather than sending data to node v_a to cache. They gain desired data blocks using the strategy $\Theta_2 = \{ec\}$ and Θ_2 is an optimal strategy for contact nodes v_a and v_p.
3. When node v_a encounters node v_p, if the fuzzy payoffs of the transmission bandwidth of node v_a and v_p are medium or high at time t, and the fuzzy payoff of the cache space of node v_p is low at time t, the requester node v_a will choose the cache action without distributing data to node v_p, while the responder node v_p will choose to distribute data to node v_a. They gain desired data blocks using strategy space $\Theta_3 = \{ce\}$ and Θ_3 is an optimal strategy for contact nodes v_a and v_p.
4. When node v_a contacts v_p, if the fuzzy payoffs of the transmission bandwidth for nodes v_a and v_p are low at time t, they do not distribute data blocks . Their strategy space is $\Theta_4 = \{cc\}$ and Θ_4 is an optimal strategy for contact nodes v_a and v_p. Thus, Θ_4 is an optimal strategy for contact nodes v_a and v_p.

4.2. Analysis of the stability of cooperative data delivery for expected fuzzy payoff matrix

In this section, we consider a v_a-v_p player zero sum game in which two players cooperate by choosing actions over their own strategy spaces and receive fuzzy payoffs. Taking the fuzzy payoffs of bandwidth and cache space into account, we can write the expected fuzzy payoff matrix u_f as follow:

		Responder	
		Distribute($\theta(t)$)	Cache($1 - \theta(t)$)
Requester	Distribute($\varepsilon(t)$)	$E\left[b_a^{ee}\right], E\left[b_p^{ee}\right]$	$E\left[h_a^{ec}\right], E\left[b_p^{ec}\right]$
	Cache($1 - \varepsilon(t)$)	$E\left[b_a^{ce}\right], E\left[h_p^{ce}\right]$	0, 0

4.2.1. Equation of replicator dynamics for fuzzy payoff of requester v_a nodes

Contact nodes are continuously moving on the road. Thus, we use a replicator equation to describe the player cooperative behavior that is imitated by other nodes involved in cooperative data delivery.

The expected fuzzy payoff obtained when the requester v_a nodes select the distribution action is:

$$E\left[U_a^e\right] = \theta(t)E\left[b_a^{ee}\right] + (1-\theta(t))\,E\left[h_a^{ec}\right] = \theta(t)E\left[b_a^{ee}\right] + E\left[h_a^{ec}\right] - \theta(t)E\left[h_a^{ec}\right], \quad (5)$$

where $\theta(t)$ is the probability for the responder v_p nodes to select the distribution strategy and $1-\theta(t)$ is the probability for v_p nodes to select the cache strategy. $\theta(t)$ is time-varying and can be estimated as the proportion of responder nodes that select the distribution action in multiple requester-responder node pairs.

The expected fuzzy payoff obtained when the requester v_a nodes select the cache action is:

$$E\left[U_a^c\right] = \theta(t)E\left[b_a^{ce}\right] + (1-\theta(t))\cdot 0 = \theta(t)E\left[b_a^{ce}\right]. \quad (6)$$

The average expected fuzzy payoff of the requester v_a nodes is:

$$E\left[\overline{U_a^{ec}}\right] = \varepsilon(t)E\left[U_a^e\right] + (1-\varepsilon(t))\,E\left[U_a^c\right], \quad (7)$$

where $\varepsilon(t)$ is the probability that the requester v_a nodes select the distribution strategy and $1-\varepsilon(t)$ is the probability that v_a nodes select the cache strategy. $\varepsilon(t)$ is variable with time-varying.

The replicator equation for the fuzzy payoff of the requester v_a nodes is:

$$\begin{aligned} n_a(\varepsilon(t)) = \tfrac{d\varepsilon(t)}{dt} &= \varepsilon(t)\left(E\left[U_a^e\right] - E\left[\overline{U_a^{ec}}\right]\right) \\ &= \varepsilon(t)\left(\theta(t)E\left[b_a^{ee}\right] + E\left[h_a^{ec}\right] - \theta(t)E\left[h_a^{ec}\right] - \varepsilon(t)\theta(t)E\left[b_a^{ee}\right] - \varepsilon(t)E\left(h_a^{ec}\right) + \varepsilon(t)\theta(t)E\left[h_a^{ec}\right] - \theta(t)E\left[b_a^{ce}\right] + \varepsilon(t)\theta(t)E\left[b_a^{ce}\right]\right) \\ &= \varepsilon(t)\left(1-\varepsilon(t)\right)\left[\theta(t)\left(E\left[b_a^{ee}\right] - E\left[b_a^{ce}\right] - E\left[h_a^{ec}\right]\right) + E\left[h_a^{ec}\right]\right]. \end{aligned} \quad (8)$$

4.2.2. Equation of replicator dynamics for the fuzzy payoff of the responder v_p nodes

The expected fuzzy payoff obtained when the responder v_p nodes select the distribution action is:

$$E\left[U_p^e\right] = \varepsilon(t)E\left[b_p^{ee}\right] + (1-\varepsilon(t))\,E\left[h_p^{ce}\right] = \varepsilon(t)E\left[b_p^{ee}\right] + E\left[h_p^{ce}\right] - \varepsilon(t)E\left[h_p^{ce}\right]. \quad (9)$$

The expected fuzzy payoff obtained when the responder v_p nodes select the cache action is:

$$E\left[U_p^c\right] = \varepsilon(t)E\left[b_p^{ec}\right] + (1-\varepsilon(t))\cdot 0 = \varepsilon(t)E\left[b_p^{ec}\right]. \quad (10)$$

The average expected fuzzy payoff of the responder v_p nodes is:

$$E\left[\overline{U_p^{ec}}\right] = \theta(t)E\left[U_p^e\right] + (1-\theta(t))\,E\left[U_p^c\right]. \quad (11)$$

The replicator equation for the fuzzy payoff of the responder v_p nodes is:

$$\begin{aligned} n_p(\theta(t)) = \tfrac{d\theta(t)}{dt} &= \theta(t)\left(E\left[U_p^e\right] - E\left[\overline{U_p^{ec}}\right]\right) \\ &= \theta(t)\left(\varepsilon(t)E\left[b_p^{ee}\right] + E\left[h_p^{ce}\right] - \varepsilon(t)E\left[h_p^{ce}\right] - \varepsilon(t)\theta(t)E\left[b_p^{ee}\right] - \theta(t)E\left[h_p^{ce}\right] + \varepsilon(t)\theta(t)E\left[h_p^{ce}\right] - \varepsilon(t)E\left[b_p^{ec}\right] + \varepsilon(t)\theta(t)E\left[b_p^{ec}\right]\right) \\ &= \theta(t)\left(1-\theta(t)\right)\left[\varepsilon(t)\left(E\left[b_p^{ee}\right] - E\left[b_p^{ec}\right] - E\left[h_p^{ce}\right]\right) + E\left[h_p^{ce}\right]\right]. \end{aligned} \quad (12)$$

4.3. ESS of fuzzy payoff for requester v_a nodes

According to the equation(8), if $E\left[b_a^{ce}\right] > E\left[b_a^{ee}\right]$ and $\theta(t) = \frac{E\left[h_a^{ec}\right]}{E[h_a^{ec}]+E[b_a^{ce}]-E[b_a^{ee}]}$, then $n_a(\varepsilon(t)) = 0$. This means that any value of $\varepsilon(t)$ is stable.

Theorem 1 When $\theta(t) > \frac{E\left[h_a^{ec}\right]}{E[h_a^{ec}]+E[b_a^{ce}]-E[b_a^{ee}]}$, then $\varepsilon(t)_1^* = 0$ is an evolutionary stable strategy (ESS).

Proof Mathematically, the stability theory of differential equations implies that if $\varepsilon(t)_1^*$ is a stable state, then $n_a'\left(\varepsilon(t)_1^*\right)$ must be less than 0. The derivative of $n_a\left(\varepsilon(t)_1^*\right)$ can be written as:

$$n_a'\left(\varepsilon(t)_1^*\right) = \theta(t)\left(E\left[b_a^{ee}\right] - E\left[b_a^{ce}\right] - E\left[h_a^{ec}\right]\right) + E\left[h_a^{ec}\right] - 2\varepsilon(t)_1^*\theta(t)\left(E\left[b_a^{ee}\right] - E\left[b_a^{ce}\right] - E\left[h_a^{ec}\right]\right) - 2\varepsilon(t)_1^*E\left[h_a^{ec}\right]. \quad (13)$$

Setting $\varepsilon(t)_1^* = 0$ and using $n_a'\left(\varepsilon(t)_1^*\right) < 0$, we have:

$$n_a'(0) = \theta(t)\left(E\left[b_a^{ee}\right] - E\left[b_a^{ce}\right] - E\left[h_a^{ec}\right]\right) + E\left[h_a^{ec}\right] < 0. \quad (14)$$

From the above, we find that $\theta(t) > \frac{E\left[h_a^{ec}\right]}{E[h_a^{ec}]+E[b_a^{ce}]-E[b_a^{ee}]}$, so $\varepsilon(t)_1^* = 0$ is an ESS. Similar to the previous proof,when $0 < \theta(t) < \frac{E\left[h_a^{ec}\right]}{E[h_a^{ec}]+E[b_a^{ce}]-E[b_a^{ee}]}$, then $\varepsilon(t)_2^* = 1$ an ESS.

4.4. ESS of fuzzy payoff for responder v_p nodes

According to the equation(12), if $E\left[h_p^{ce}\right] > E\left[b_p^{ee}\right]$ and $\varepsilon(t) = \frac{E\left[h_p^{ce}\right]}{E\left[b_p^{ec}\right]+E\left[h_p^{ce}\right]-E\left[b_p^{ee}\right]}$, then $n_p\left(\theta(t)\right) = 0$. This means that the evolutionary state is stable for any value of $\theta(t)$.

Theorem 2 When $\varepsilon(t) > \frac{E\left[h_p^{ce}\right]}{E\left[b_p^{ec}\right]+E\left[h_p^{ce}\right]-E\left[b_p^{ee}\right]}$, then $\theta(t)_1^* = 0$ is an ESS.

Proof Similar to the previous proofs, if $\theta(t)_1^*$ is a stable state, then $n_p'\left(\theta(t)_1^*\right)$ must be less than 0. The derivative of $n_p\left(\theta(t)_1^*\right)$, can be written as:

$$n_p'\left(\theta(t)_1^*\right) = \varepsilon(t)\left(E\left[b_p^{ee}\right] - E\left[b_p^{ec}\right] - E\left[h_p^{ce}\right]\right) + E\left[h_p^{ce}\right] - 2\theta(t)_1^*\varepsilon(t)\left(E\left[b_p^{ee}\right] - E\left[b_p^{ec}\right] - E\left[h_p^{ce}\right]\right) - 2\theta(t)_1^* E\left[h_p^{ce}\right]. \quad (15)$$

Setting $\theta(t)_1^* = 0$ and using $n_p'\left(\theta(t)_1^*\right) < 0$, we have:

$$n_p'(0) = \varepsilon(t)\left(E\left[b_p^{ee}\right] - E\left[b_p^{ec}\right] - E\left[h_p^{ce}\right]\right) + E\left[h_p^{ce}\right] < 0. \quad (16)$$

From the above, we find that $\varepsilon(t) > \frac{E\left[h_p^{ce}\right]}{E\left[b_p^{ec}\right]+E\left[h_p^{ce}\right]-E\left[b_p^{ee}\right]}$, then $\theta(t)_1^* = 0$ is an ESS. Similar to the previous proofs, when $0 < \varepsilon(t) < \frac{E\left[h_p^{ce}\right]}{E\left[b_p^{ec}\right]+E\left[h_p^{ce}\right]-E\left[b_p^{ee}\right]}$, then $\theta(t)_2^* = 1$ is an ESS.

5. Nash equilibrium conditions of game payoff for contact nodes

5.1. Payoff of players when taking different strategies

When nodes take different strategies, their payoffs are different. If contact nodes v_a and v_p take the strategy Θ_1, the payoff of the requester node v_a is:

$$U\left(v_a, \Theta_1\right) = \frac{m_a + m_p}{m_a} B_g - (m_a + m_p)B - m_a\sigma. \quad (17)$$

The first component on the right of the equation is the relative gain obtained through the shared data, where the numerator is the total number of data blocks owned by the requester node v_a after taking the strategy Θ_1 and the denominator is the original number of data blocks of the requester node v_a. B_g is the gain factor of cooperation to share data between contact nodes. The second component is the cost taken to cache the data block in v_a, where B denotes the cache resources used per bit. The third component is the energy cost to transmit the data, where the power required for the data distribution is $m_a\sigma$, with σ being the power resources used per bit.

Similarly, the payoff of the responder node v_p by assuming the strategy Θ_1 is:

$$U\left(v_p, \Theta_1\right) = \frac{m_p + m_a}{m_p} B_g - (m_p + m_a)B - m_p\sigma. \quad (18)$$

When contact nodes v_a and v_p take the strategy Θ_2, the size of the data blocks distributed by v_a is m_a. The cost of requester node v_a for data distribution and caching is $m_aB + m_a\sigma$. The payoff of the requester node v_a can be represented as:

$$U\left(v_a, \Theta_2\right) = B_g - m_aB - m_a\sigma. \quad (19)$$

Similarly, the game payoff of the responder node v_p when taking the strategy Θ_2 is:

$$U\left(v_p, \Theta_2\right) = \frac{m_p + m_a}{m_p} B_g - (m_p + m_a)B. \quad (20)$$

When contact nodes v_a and v_p take the strategy Θ_3, the size of the data blocks distributed by v_p is m_p. The cost of the responder node v_p for data distribution and caching is $m_pB + m_p\sigma$. The game payoff of the requester node v_a is:

$$U\left(v_a, \Theta_3\right) = \frac{m_a + m_p}{m_a} B_g - (m_a + m_p)B. \quad (21)$$

The game payoff of the responder node v_p is:

$$U\left(v_p, \Theta_3\right) = B_g - m_p B - m_p \sigma. \tag{22}$$

When contact nodes v_a and v_p take the strategy Θ_4, the size of the data blocks distributed by v_a and v_p is 0. The game payoff of the requester node v_a is:

$$U\left(v_a, \Theta_4\right) = B_g - m_a B. \tag{23}$$

The game payoff of the responder node v_p is:

$$U\left(v_p, \Theta_4\right) = B_g - m_p B. \tag{24}$$

5.2. Nash equilibrium conditions of game payoff

No matter what strategy v_a and v_p select, when the requester node v_a contacts the responder node v_p, they estimate the payoff of cooperative strategies. If the payoff of distributing data blocks is greater than that of caching data blocks for the requester node v_a, it must select Θ_1 as the dominant strategy under a rational cooperation decision, which is the unique equilibrium of the game. The Nash equilibrium condition of the game payoff for the requester node v_a is:

$$U\left(v_a, \Theta_1\right) > U\left(v_a, \Theta_3\right), U\left(v_a, \Theta_2\right) > U\left(v_a, \Theta_4\right). \tag{25}$$

If the fuzzy payoff of distributing data blocks is greater than the payoff of caching data blocks for the responder node v_p , then Θ_1 must be selected as the dominant strategy under a rational cooperation decision, which is the unique equilibrium of the game. The Nash equilibrium condition of game payoff for the requester node v_p is:

$$U(v_p, \Theta_1) > U(v_p, \Theta_2), U(v_p, \Theta_3) > U(v_p, \Theta_4). \tag{26}$$

6. Cooperative data delivery optimization

We consider a discrete contact time model in which the time horizon is divided into T time slots. Each node has a set of actions to choose as cooperative data delivery strategies. We consider the cost for using the cache space and the distribution time. The cooperative data delivery strategies can be imitated by other contact nodes through our evolutionary fuzzy game. We define a binary variable x^t to denote whether a data block is cached at time t:

$$x^t = \begin{cases} 1, & if\ m_a + m_p > 0\ \ or\ \ m_p + m_a > 0, \\ 0, & otherwise. \end{cases} \tag{27}$$

The cache occupation cost can be calculated as follows:

$$C = B \sum_{t=1}^{T} \left((m_a + m_p) \cdot 1_{\{m_a + m_p > 0\ \}} + (m_p + m_a) \cdot 1_{\{m_p + m_a > 0\}} \right), \tag{28}$$

where $\mathbf{1}_{\{m_a + m_p > 0\ \}}$ is the indicator function, which is equal to 1 if a data block is cached by node v_a and 0 otherwise. $\mathbf{1}_{\{m_p + m_a > 0\}}$ is the indicator function, which is equal to 1 if a data block is cached by node n_p and 0 otherwise.

We also define a binary variable y^t to indicate whether a data block is distributed at time t:

$$y^t = \begin{cases} 1, & if\ m_a > 0\ \ or\ \ m_p > 0, \\ 0, & otherwise. \end{cases} \tag{29}$$

The distribution cost of data blocks can be calculated as follows:

$$D = \sigma \sum_{t=1}^{T} \left(m_a \cdot 1_{\{m_a > 0\}} + m_p \cdot 1_{\{m_p > 0\}} \right), \tag{30}$$

where the indicator function $\mathbf{1}_{\{m_a > 0\}}$ is equal to 1 if a data block is distributed by node v_a and 0 otherwise. The indicator function $\mathbf{1}_{\{m_p > 0\}}$ is equal to 1 if a data block is distributed by node v_p and 0 otherwise.

With the Nash equilibrium conditions of the data delivery, the cooperative data delivery optimization problem is to minimize the cost of the cache occupation and distribution of data block:

$$\begin{aligned} &\min_{x^t, y^t, \Theta} C_{total} = C + D \\ &s.t. \;\; (x^t + y^t) \geq \mu_t, t = 1, 2, .., T, \quad (24a) \\ &\qquad (25) - (26), \qquad\qquad\qquad\quad (24b) \\ &\qquad x^t, y^t \in \{1, 0\}, t = 1, 2, .., T. \quad (24c) \end{aligned} \tag{31}$$

where μ_t is a binary indicator that denotes the flow rate in time t, whose value is equal to 1 if a data block is distributed and 0 otherwise. The constraint (24a) ensures that arriving data blocks be processed by either caching or distribution. Constraint (24b) ensures that the contact nodes to satisfy the Nash equilibrium conditions. We can use an evolutionary equation to adjust the cost parameters C and D to minimize the total cost. The evolutionary equations on the lengths of the cache queues for nodes v_a and v_p are given by:

$$\begin{cases} Q_a^{t+1} = Q_a^t + m_p, \\ Q_p^{t+1} = Q_p^t + m_a. \end{cases} \tag{32}$$

Let α_a^t $(0 < \alpha_a^t < 1)$ and $\beta_p^t \left(0 < \beta_p^t < 1\right)$ denote the factor of the delivery rate, r is the interface transmission rate of nodes v_a and v_p, i.e., using $\alpha_a^t r$ or $\beta_p^t r$ to control the interface transmission rate of nodes v_a and v_p, respectively. Let τ_a^t denote the time duration allocated by the requester node v_a to distribute data blocks, τ_p^t denote the time duration allocated by the responder node v_p to distribute data blocks, and $\tau_a^t + \tau_p^t \leq T$. If $\tau_a^t > T - \tau_p^t$, node v_a can not complete the data block distribution during τ_p^t. So, increasing the the factor of the delivery rate α_a^t $(0 < \alpha_a^t < 1)$ by $\Delta\alpha_a^t$ to control the rate of delivering will increase the distribution capacity of the requester node v_a. Otherwise, if $\tau_p^t > T - \tau_a^t$, increasing the factor of the delivery rate $\beta_p^t \left(0 < \beta_p^t < 1\right)$ by $\Delta\beta_p^t$ to control the rate of delivering will increase the distribution capacity of the responder node v_p. The evolutionary equation for the distribution factor to minimize delay time is given by:

$$\begin{cases} \alpha_a^{t+1} = \alpha_a^t + \Delta\alpha_a^t, \; if \;\; \tau_a^t > T - \tau_p^t, \\ \beta_p^{t+1} = \beta_p^t + \Delta\beta_p^t, \; if \;\; \tau_p^t > T - \tau_a^t. \end{cases} \tag{33}$$

6.1. Adaptive cooperative data delivery strategies

Due to the dynamic nature of VANETs, the proposed fuzzy payoff inference system must be modified to handle variation of the contact time. Fig.4 shows an overview of the proposed cooperative data delivery optimization process, starting with the online fuzzy payoff inference to determine the optimal strategy, as described in the previous section. After the online fuzzy payoff inference, a fuzzy rule base is used to select the cooperative data delivery strategy and perform a suitable action. When a requester node contacts other responder nodes, this fuzzy rule base is loaded into the nodes and new fuzzy payoff inputs are shared to predict the cooperative payoff level. However, the Nash equilibrium conditions in the new network may have changed, and the system should adapt to this by triggering the online adaptation fuzzy inference module and the cache queue updating algorithm. The steps involved in the online creation of the new rule base and fuzzy payoff level classification with online real-time cooperative data delivery are as follows.

Step 1. A requester node v_a exchanges the bandwidth and cache space payoffs with the responder contact node v_p. The fuzzy payoff inference system takes the new inputs b_a^{ee}, b_a^{ce}, h_a^{ec}, b_p^{ee}, h_p^{ce}, and b_p^{ec}. First, the value of Pr (i.e., the function of the fuzzy membership) is computed by each node. Then, the rule is used to infer the fuzzy payoff level. The fuzzy set that contains the maximum values of the function of fuzzy membership at the data point is the selected strategy Θ_i^* from the set of strategies Θ. Then, contact nodes perform the optimal action.

Step 2. When a new node appears on the road, it joins the contact graph consisting of neighboring nodes and infers its fuzzy payoff level to gain the desired data.

Step 3. Compute the cache queue, the time duration needed for data transmission (i.e., $\tau_a^t = \frac{m_a}{\alpha_a^t r}$ and $\tau_p^t = \frac{m_p}{\beta_p^t r}$), and the game payoff for nodes v_a and v_p after determining the optimal action. When the game payoff $U(v_a, \Theta_1)$ is greater than $U(v_a, \Theta_3)$ and $U(v_a, \Theta_2)$ is also greater than $U(v_a, \Theta_4)$, the requester node v_a takes the distribution data action, and the cache queue and fuzzy rules for requester node v_a are updated. If τ_a^t is greater than $T - \tau_p^t$, the requester node v_a modifies its factor of data block distribution α_a^t. When the game payoff $U(v_p, \Theta_1)$ is greater than $U(v_p, \Theta_2)$

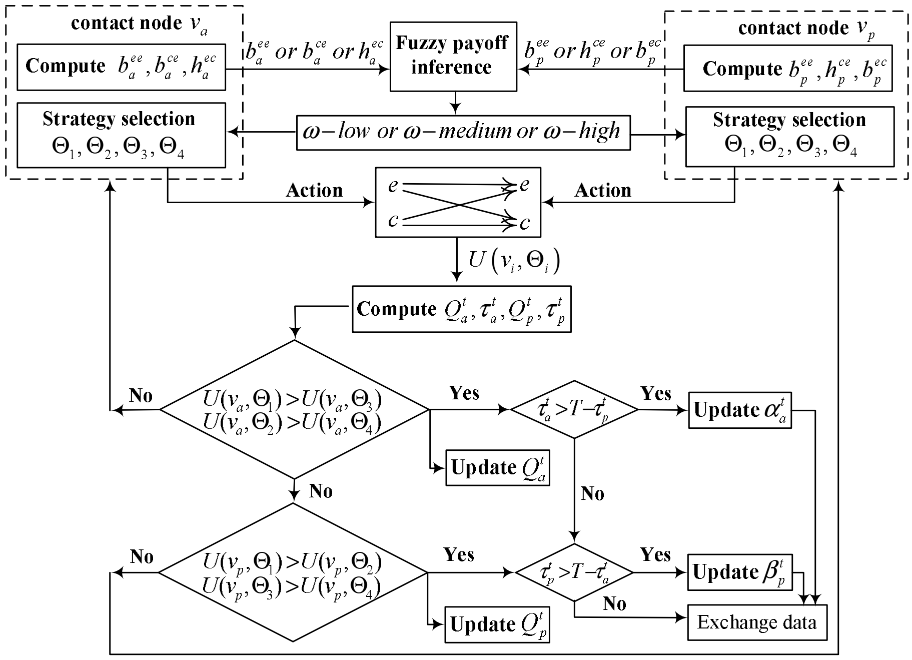

Figure 4. Flow chart of cooperative data delivery optimization process.

and $U(v_p, \Theta_3)$ is also greater than $U(v_p, \Theta_4)$, the responder node v_p takes the distribution data action, and the cache queue and fuzzy rules for the responder node v_p are updated. Then, if τ_p^t is greater than $T - \tau_a^t$, the responder node v_p modifies its factor of data block distribution β_p^t. Details of the cache queue and factor of data block distribution update process are given in Algorithm 1.

Algorithm 1: Real-time cooperative data delivery updating for V2V communications

Initialize $Q_a^t = 0$, $Q_p^t = 0$, $\tau_a^t = 0$, $\tau_p^t = 0$
Construct fuzzy rule and determine optimal action
`/* Compute the game payoff according to (18)-(25), update cache queue and data distribution time */`
foreach *time* $t \in [1, T]$ *in contact graph* G **do**
  Compute $U(v_p, \Theta_1), U(v_p, \Theta_2), U(v_p, \Theta_3), U(v_p, \Theta_4), U(v_a, \Theta_1), U(v_a, \Theta_3)$, and $U(v_a, \Theta_2), U(v_a, \Theta_4)$
  `/* Requester nodes take data distribution action */`
  if $U(v_a, \Theta_1) > U(v_a, \Theta_3)$ *and* $U(v_a, \Theta_2) > U(v_a, \Theta_4)$ **then**
    $x_p^t = 1$;`// Set responder node's indicator of cache`
    $y_a^t = 1$;`// Set requester node's indicator of data distribution`
    Update Q_a^{t+1} using (32);`// Update requester node's cache queue`
    if $\tau_a^t > T - \tau_p^t$ **then**
      Update α_a^t using (33);`// Update requester node's distribution rate factor`
    end
  `/* Responder nodes take data distribution action */`
  else if $U(v_p, \Theta_1) > U(v_p, \Theta_2)$ *and* $U(v_p, \Theta_3) > U(v_p, \Theta_4)$ **then**
    $x_a^t = 1$; `// Set requester node's indicator of cache`
    $y_p^t = 1$; `// Set responder node's indicator of data distribution`
    Update Q_p^{t+1} using (32);`// Update responder node's cache queue`
    if $\tau_p^t > T - \tau_a^t$ **then**
      Update β_p^t using (33);`// Update responder node's distribution rate factor`
    end
  end
end

7. Simulations

We evaluate the performance of the proposed cooperative data distribution model via Matlab and NS2. The parameters used in the simulations are introduced along with each study. Because of the chosen payoff measurement unit, all parameter values are normalized to be within [0, 1].

Because Matlab tool can simulate the game stability and fuzzy system, we implement an evolutionary game model and ***Does matlab have the game model?*** apply it to evaluate the stability of the evolutionary game and fuzzy inference. We perform the following sets of studies :(1) We set different values for the expected payoffs to show how contact nodes change their game strategies to avoid the buffer overflow. (2) We vary the distribution probability for the requesters to verify the evolutionary stability of the expected fuzzy payoffs at v_a and v_p nodes. (3) We set the different expected payoffs to infer the bandwidth level. We use the "gaussmf" membership function for the fuzzy bandwidth payoff inference and "gbellmf" for the fuzzy cache space payoff inference. ***How did you infer the bandwidth?***

We further evaluate the effectiveness of our data forwarding model to support data distributions in VANET using the NS2 simulator version 2.35. NS2 is a simulator widely used for wireless network research. We evaluate the data delivery delay and distribution rate of eight requester-responder node pairs in the neighborhood by comparing the cooperative data delivery in the contact time with the non-cooperative data delivery.***Did you only have four node pairs or you simulate four node pairs in the neighborhood.? What do you mean based on the contact time? Throughput this section, I don't know what you mean "with the contact time" How many moving nodes? Instead of saying random distribution within a area, which is not the case of VANET, you may check other VANET papers and see how they simulate the node distribution. You may refer to the same set up.*** In the simulation scenarios, the road topology consists of a two-lane and two-way road of length 15km. Vehicles are deployed in the road with a predefined traffic flow, IEEE 802.11 standard for wireless access in vehicular environments with 1 MB channel rate was employed. We considered a data block to be disseminated in unicast sessions. Each data block contains packets of either 1500 or 1000 bytes. The average speed of vehicle movement is 40m/s, which is considered a regular speed on the road. Because the mobility of nodes leads to the change of bandwidth, this impact the performance of cooperative data delivery. So, we infer bandwidth payoffs to overcome the effect of the mobility of nodes. ***Why this MAC? This is not for VANET. 802.11p is. By multicast, you mean one node sends data to multiple receivers? This does not seem to be the model you use in this paper. Will mobility impact the performance?***

We focus on the reliable data delivery rate in the V2V mode considering the vehicles' cooperation and compare the proposed cooperative data delivery method, obtained by Algorithm 1, with three peer strategies the Least Recently Used (LRU) caching algorithm[38], Local Greedy Caching (LGC) strategy [39], and the Local Caching Algorithm (LCA)[40].

7.1. Evolutionary stability of the expected fuzzy payoff at nodes v_a and v_p

For the requester node v_a, we set the parameter values as follows: $E\left[b_a^{ee}\right] = 0.66$, $E\left[b_a^{ce}\right] = 0.45$, so that $E\left[b_a^{ce}\right] < E\left[b_a^{ee}\right]$. Fig. 5 shows that, as the value of θ increases, the v_a node can better resist small deviations in the cache overflow How did you observe this from the figure? by using the game strategy, ***What strategy will Va take?*** and eventually converge to $\varepsilon^* = 1$. This is because that contact nodes v_a and v_p take the distribution strategy $\Theta_1 = \{ee\}$ to gain the desired data blocks and then contact nodes v_a and v_p update their cache queue.

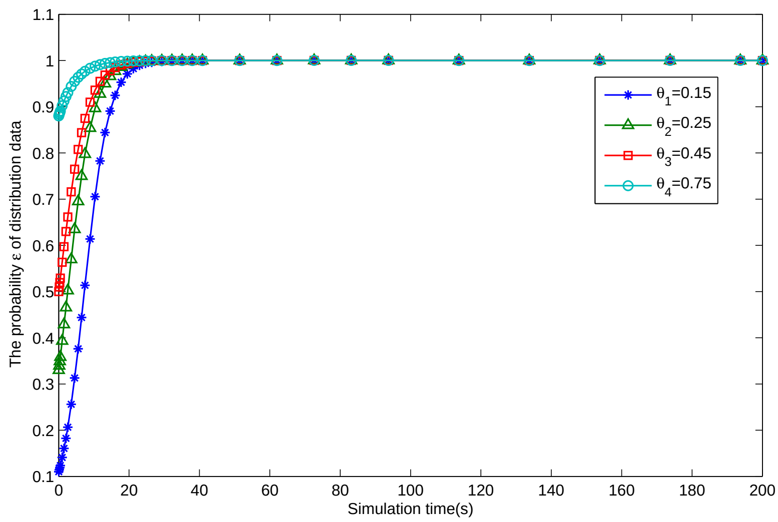

Figure 5. The ESS of requester v_a nodes when $E\left[b_a^{ce}\right] < E\left[b_a^{ee}\right]$.

For v_p nodes, we set $E\left[b_p^{ee}\right] = 0.4$, $E\left[b_p^{ec}\right] = 0.1$, that is, $E\left[b_p^{ee}\right] > E\left[b_p^{ec}\right]$. Fig. 6 shows that larger values of ε allow the v_p nodes ***multiple nodes*** to resist small deviations in the cache overflow by using the game strategy, and eventually converge to $\theta^* = 1$.

We vary the probability ε of the data distribution actions taken by the v_a nodes in the range 0.15-0.50. Fig. 7 shows that the v_p nodes can resist small deviations in the cache overflow by using the game strategy. When $\varepsilon < 0.25$, the system eventually converges to the state $\theta^* = 0$. For $\varepsilon = 0.25$, the probability θ for a v_p nodes to take the data distribution action remains unchanged at 0.33. However, when $\varepsilon = 0.50$, the v_p nodes eventually converges to the state $\theta^* = 1$.

Are you using plural "nodes" or single "node"? You did not make it clear in the setting, and also did not make it consistent in the same presentation part. Also, don't use past state in the performance studies.

For responder v_p nodes, we also set $E\left[b_p^{ee}\right] = 0.1$, $E\left[b_p^{ec}\right] = 0.4$, that is, $E\left[b_p^{ee}\right] < E\left[b_p^{ec}\right]$, and vary ε over the range 0.15-0.50. From Fig. 8, we can see that the v_p nodes could again resist small deviation in the cache overflow by using

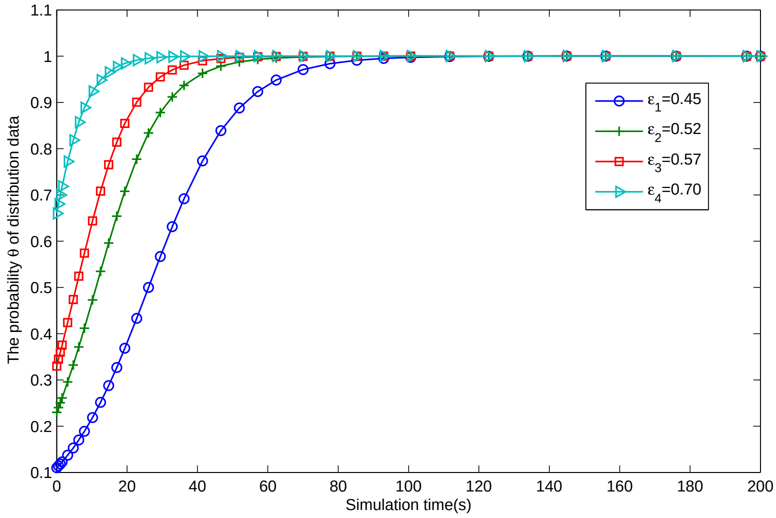

Figure 6. The ESS of responder v_p nodes for different the value of ε when $E\left[b_p^{ee}\right] > E\left[b_p^{ec}\right]$.

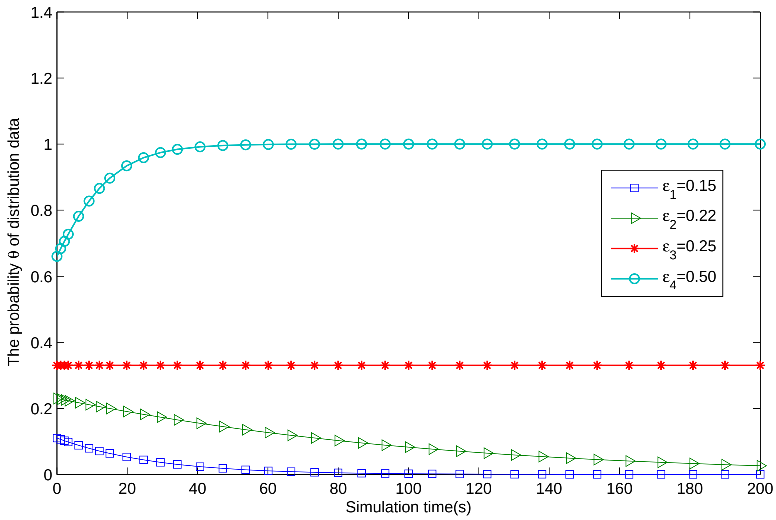

Figure 7. The ESS of responder v_p nodes for different the value of ε.

the game strategy, and eventually converges to the state $\theta^* = 0$. For the requester v_a nodes, we set the parameters to $E\left[b_a^{ee}\right] = 0.36$, $E\left[b_a^{ce}\right] = 0.45$, and $E\left[h_a^{ec}\right] = 0.3$, that is, $E\left[b_a^{ce}\right] > E\left[b_a^{ee}\right]$. For various values of θ, Fig. 9 shows that the requester v_a nodes can resist small deviations in the cache overflow by using the game strategy, and eventually converges to the state $\varepsilon^* = 0$.

Check the conditions of Figure 5 and 9. They are not consistent with the paper texts.

7.2. Evolutionary stability of expected payoff of v_a and v_p nodes for distribution rate factor

We examine how the distribution rate taken by requesters and responders affect the performance of the cooperative data delivery algorithms. Given $m_a = 3GB$, $m_p = 8GB$, $B = 0.1bits$, $\sigma = 0.1dBm$, and $T = 6s$, with 8 requesters and 8 responders, we have eight pairs of contact nodes. Fig. 10 indicates that, when $\alpha_7 = 0.80$, $\beta_7 = 0.10$, $\theta_7 = 0.72$,

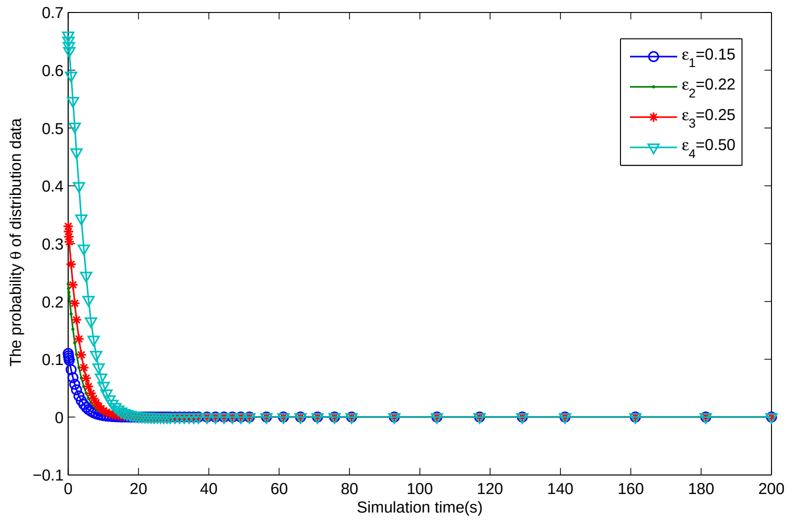

Figure 8. The ESS of responder v_p nodes when $E\left[b_p^{ee}\right] < E\left[b_p^{ec}\right]$.

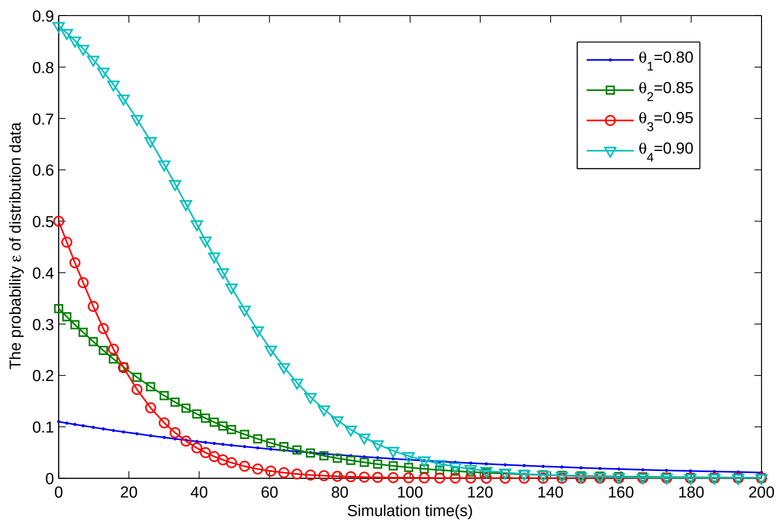

Figure 9. The ESS of requester v_a nodes when $E\left[b_a^{ce}\right] > E\left[b_a^{ee}\right]$.

$\alpha_8 = 0.80, \beta_8 = 0.77$, and $\theta_8 = 0.72$, the data distribution probability of the requester v_{a7} and v_{a8} nodes becomes 0. This is because, the cache space of nodes v_{p7} and v_{p8} are low, the distribution data probability of the responder v_{p7} and v_{p8} nodes reaches 0.72, the requesters v_{a7} and v_{a8} change their distribution actions to the cache actions to receive data from responder nodes v_{p7} and v_{p8}. In addition, when $\alpha_4 = 0.20, \beta_4 = 0.80, \theta_4 = 0.38$, the data distribution probability of the requester v_{a4} also falls to 0. This is because the data distribution probability for the responder v_{p4} has reduced to 0.38, but the data distribution factor α_4 is less than β_4, so the requester v_{a4} node again changes from a distribution to a cache action to receive data. From the above phenomenon, we notice that changing $\theta_8 = 0.72$ to $\theta_4 = 0.38$ causes the distribution rate factor α_4 of the requester v_{a4} node to become less than β_4 of the responder v_{p4}. Thus, the requester v_{a4} must change from a distribution action to a cache action. Fig.10 shows that, when $\alpha_6 = 0.01, \beta_6 = 0.72$ and $\theta_6 = 0.77$,

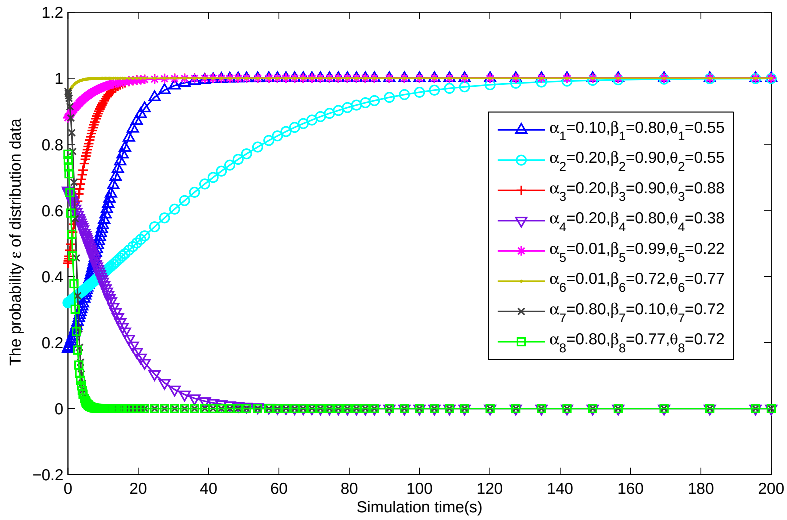

Figure 10. The ESS of expected payoff of cooperative data delivery when $\sigma = 0.1dBm$ and $T = 6s$.

the requester v_{a6} node can distribute data considerably faster than the node v_{a3} when $\alpha_3 = 0.20, \beta_3 = 0.90, \theta_3 = 0.88$. This is because the distribution data factor α_6 is less than α_3 for the requester v_a nodes, and data delivery can thus be completed in a shorter time. When $\alpha_2 = 0.20, \beta_2 = 0.90, \theta_2 = 0.55$, Fig.10 shows that the requester v_{a2} attains a stable state using the distribution action considerably slower than the requester v_{a6} when $\alpha_6 = 0.01, \beta_6 = 0.72, \theta_6 = 0.77$, because the data distribution probability θ_2 of the responder v_{p2} node is less than the data distribution probability θ_6 of the responder v_{p6} node, and the distribution rate factor α_2 is greater than α_6, which results in long data delivery time for the requester v_a.

From Fig. 11, we can see that when the contact time is $1s$, the requester and responder node pairs (v_{a1},v_{p1}), (v_{a2},v_{p2}), (v_{a3},v_{p3}), (v_{a4},v_{p4}), (v_{a5},v_{p5}), (v_{a6},v_{p6}), and (v_{a8},v_{p8}) select the data distribution action and complete their data delivery within a short period of time. The node pair (v_{a7},v_{p7}) has a decreased probability of distributing data, because the distribution rate factor v_{p7} is far lower. From Fig. 12, we can see that when the power resources σ increase to 1 dBm, the requester and responder node pairs (v_{a1},v_{p1}) and (v_{a3},v_{p3}) are slower to distribute data and attain a stable state. The requester and responder nodes (v_{a2},v_{p2}), (v_{a4},v_{p4}), (v_{a7},v_{p7}), and (v_{a8},v_{p8}) select the cache data action. In Fig. 13, when $\sigma = 1.3dBm$, only the requester and responder nodes v_5 and v_6 select the distribution data action. This shows that the payoff under the cooperative data delivery decreases as the power resources σ increases.

7.3. Fuzzy inference of expected payoff of $E[b]$ and $E[h]$ for data block distribution

Next, we simulate the meaning of the linguistic values using membership functions. The membership functions of the linguistic variables are determined by using an intuitive choice. We select the “gaussmf” membership function for the fuzzy bandwidth payoff and “gbellmf” for the fuzzy cache space payoff in the control system. These distributions are standard choices in many industrial applications, because the mathematical expressions of gaussmf and gbellmf can represent intermittent changes of the bandwidth and cache space in VANETs. The selected membership functions representing the linguistic values for both the inputs and output of the fuzzy payoff controller are shown in Figs.14,15,16. For example, The strategy $\Theta_2 = \{ec\}$ gives an expected fuzzy payoff to the requester v_a of $E\left[h_a^{ec}\right]$ and an expected fuzzy payoff to the responder v_p nodes of $E\left[b_p^{ec}\right]$. When $E\left[h_a^{ec}\right] = 0.3$, $E\left[b_p^{ec}\right] = 0.5$, Fig. 16 shows that the fuzzy payoff is in the medium range, at 0.48. The requester v_a node will select the distribution data action and the responder v_p node will select the cache data action.

7.4. Performance evaluation of cooperative data delivery with contact time in VANETs

In the simulation, we set the contact time and delivery time to observe the cache queue changes. Fig. 17 shows the average delay with varying number of delivery packets at contact node pairs, we can see that the delivery delay of the

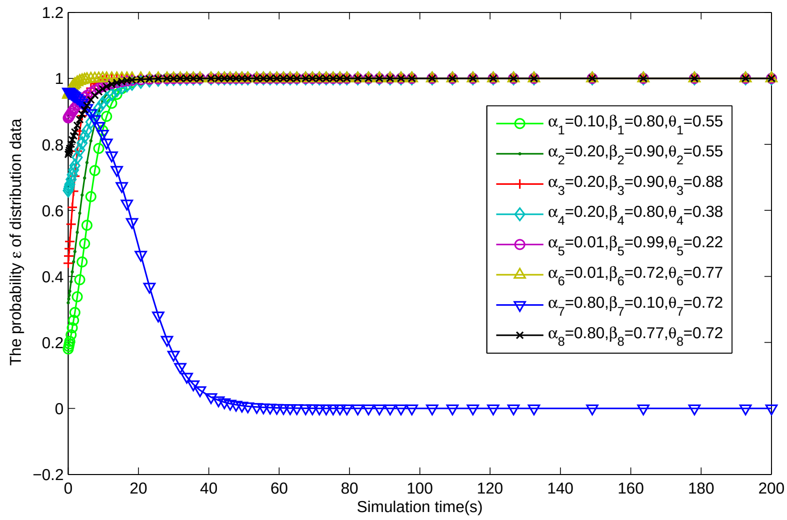

Figure 11. The ESS of expected payoff of cooperative data delivery when $\sigma = 0.1dBm$ and $T = 1s$.

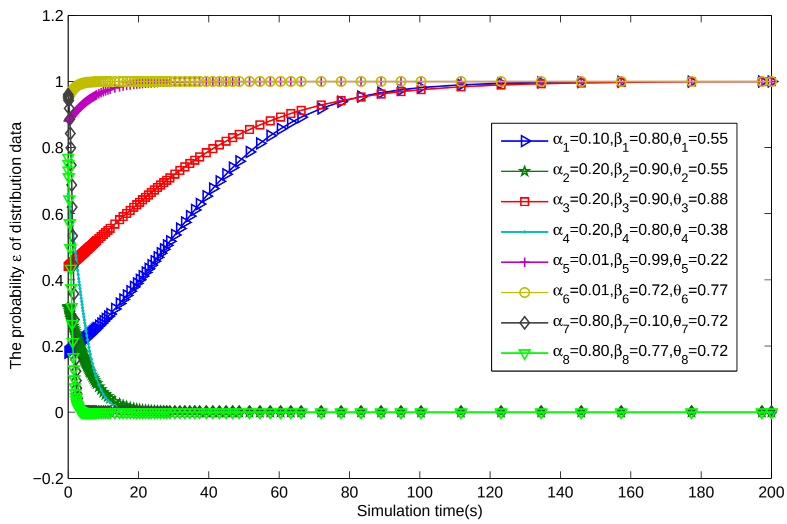

Figure 12. The ESS of expected payoff of cooperative data delivery when $\sigma = 1dBm$ and $T = 1s$.

cooperative data delivery in the contact time ***What do you mean "with contact time"? If nodes do not contact, they will have nor data delivery, right?*** is lower than that in a VANET with non-cooperative data delivery for packet ID numbers from 2.5×10^4 to 3.9×10^4. This suggests that the cooperative data delivery with the contact time has an obvious delivery improvement over the non-cooperative data delivery. This is because the cooperative data delivery selects the data delivery nodes with the short delay based on both the contact graph and the actions of peer nodes and can avoid the cache overflow thus the delivery failure. Because non-cooperative data delivery uses all the available nodes and takes delivery actions in a random manner, its delay is longer than that of the cooperative data delivery. When the number of packets is greater than 4×10^4, the delivery delay of the cooperative data delivery begins to increase. It is because the number of delivery packets dramatically increase.

Fig. 18 compares the average data distribution rate between cooperative data delivery and non-cooperative data

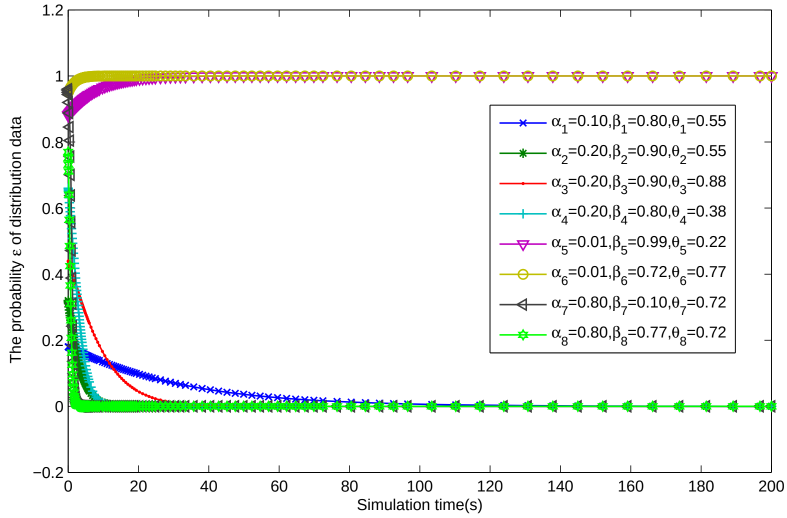

Figure 13. The ESS of expected payoff of cooperative data delivery when $\sigma = 1.3dBm$ and $T = 1s$.

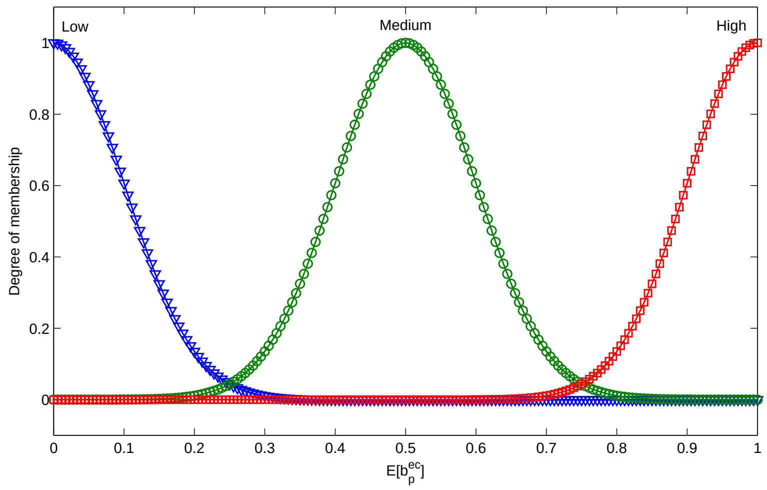

Figure 14. Bandwidth linguistic input.

delivery with varying number of delivery packets. ***In the figure, the two lines overlap, and I don't see difference. You may use semi-log figure, with Y axis shows log.(see fig.18)*** When the number of delivery packets increase, we can see that the average data distribution rate of the proposed scheme is greater than that non-cooperative data delivery in a VANET. The non-cooperative data delivery does not consider the interactions of requester and responder nodes, while the interactions have significant impact on packet losses. A contact node drops packets when its cache is filled up and does not exchange the packet with other contact nodes. On the other hands, the number of packet drops increases for both methods when the number of delivery packets increases. The cooperative data delivery always drops the fewest packets, because the strategy selections in cooperative data delivery can cache or distribute data with each other and the traffic is distributed among them according to their payoffs of the bandwidth and cache spaces. From Figs. 17 and 18, we see that the proposed algorithm in the data delivery delay and distribution rate outperforms non-cooperative data delivery by 1%, 33%, respectively.

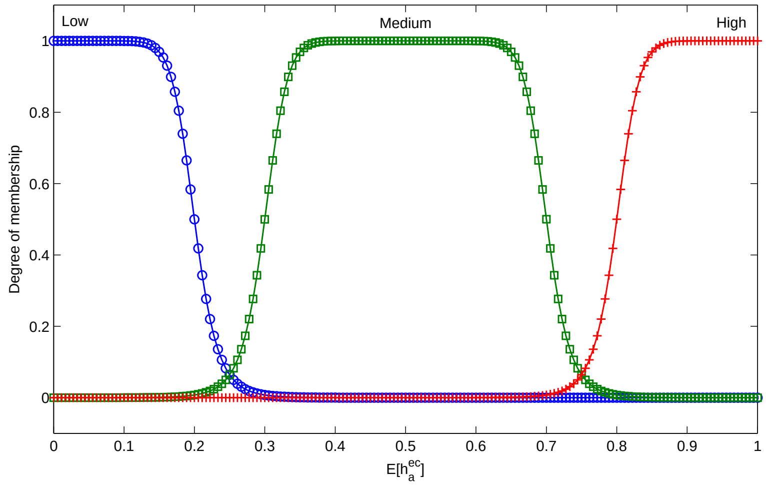

Figure 15. Cache space linguistic input.

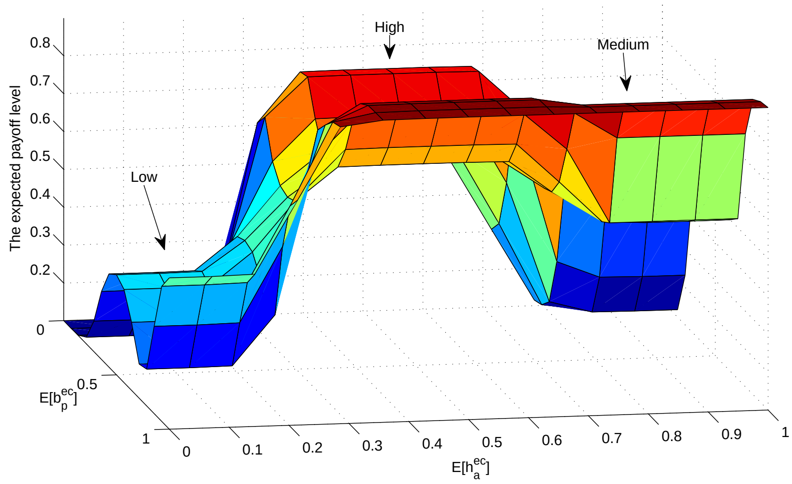

Figure 16. Decision surface of fuzzy payoff level.

In the evolutionary game model, we set different parameter to simulate LGC, LCA, and LRU methods and compare with the proposed methods in this paper, Thus, the average data delivery rate of all methods converge 1. In Fig. 19, it is observed that the average data delivery rate of the proposed cooperative data delivery method is higher than LGC at 20s. ***what do you mean "51% of the average data delivery rate"? I am not sure what rate you are referring to. I don't see this data from the figure. Also, why as time increases. all rates become 1? Then there is no difference between schemes.*** This is because the LGC strategy chooses greedily the remaining items with the largest popularity-to-size ratio to distribute until the cache at the base station (BS) is filled up, but does not take into account the data transfer bandwidth. The average data delivery rate of LGC is ***I don't see where you got this data as well.*** higher than LCA at 20s. This is because LCA exploits only the local caching gain without predicting the transfer bandwidth, LGC sorts the content items in the descending order according to their popularity-to-size ratios. The average data delivery rate of LRU is the lowest, LRU always keeps in the cache the most recently requested files without considering the caching or distribution conditions. Our proposed cooperative data delivery method distributes

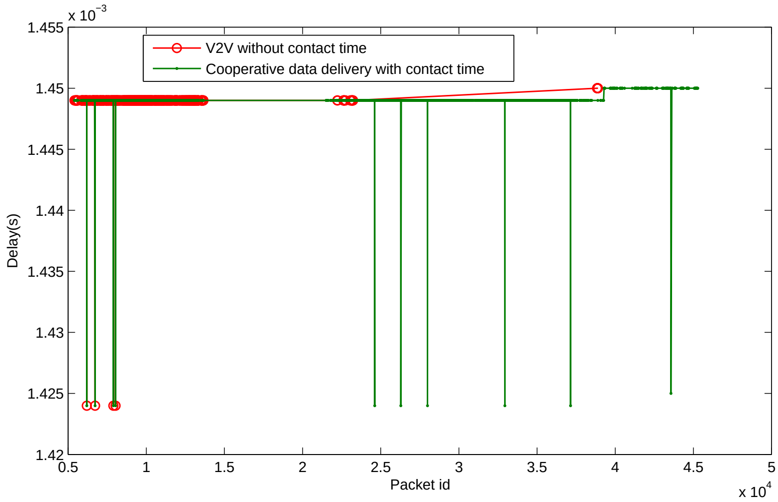

Figure 17. Delay time to delivery data block.

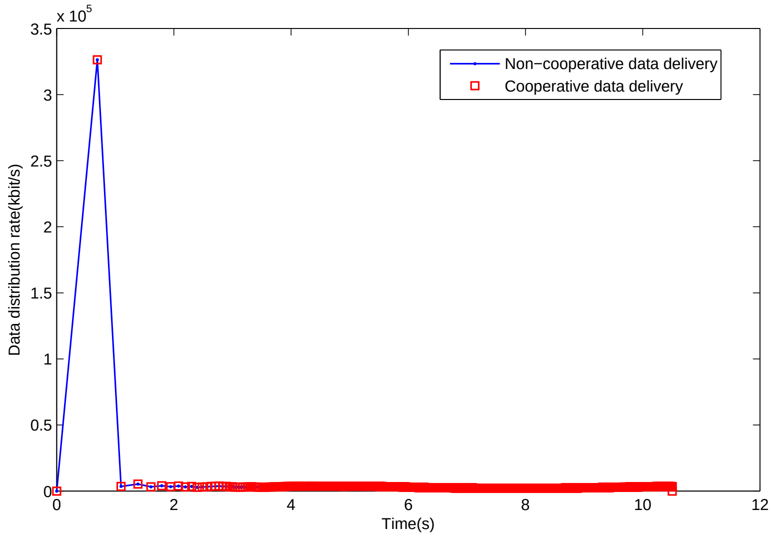

Figure 18. Data distribution rate.

data in a contact graph based on a contact rate and considers the local caching and bandwidth gains and the game payoff compared with LGC, LCA,and LRU.

8. Conclusions

In this paper, we propose to enable cooperative data delivery based on an evolutionary fuzzy game to ensure more reliable data delivery in VANETs. We consider a two-phase cooperative data delivery approach based on the contact graph. In the first stage, each requester node and responder node determine which cooperative data delivery strategy to take using fuzzy payoff inference. We propose an online real-time cooperative data delivery update method based on fuzzy payoff inference and a fuzzy payoff matrix. The second phase is conducted iteratively until the delivery action converges. We also present a real-time cooperative data delivery method in a contact graph *G* based

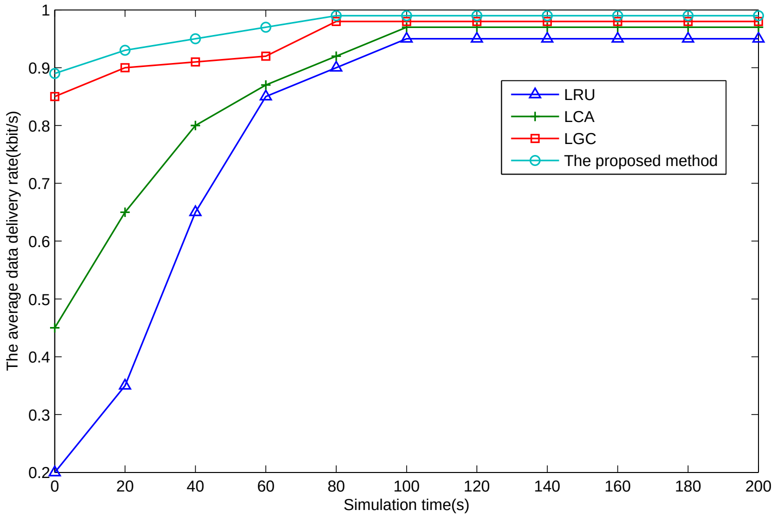

Figure 19. The reliable data delivery rate.

on the expected utility matrix and analyze the theoretical characteristics of the scheme in terms of its evolutionary stability. Simulation results show that requester/responder vehicle nodes are capable of coordinating their caching and distributing strategies for reliable data delivery in a distributed fashion, even if there is no centralized coordinating node.

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Jianhua Liu received his Ph.D. degree in computer application technology from Shanghai University, Shanghai, China, in 2012. He was a visiting scholar in the State University of New York College at Buffalo in 2014. He is an associate professor with the College of Mathematics, Physics and Information Engineering, Jiaxing University, Jiaxing, China. He is currently a postdoctoral fellow in the Department of Computer Science and Engineering, Shanghai Jiao Tong University. His research interests include distributed computing, wireless communications, multimedia networking, and wireless sensor networks.

Xin Wang received the BS and MS degrees in telecommunications engineering and wireless communications engineering, respectively from the Beijing University of Posts and Telecommunications, Beijing, China, and the PhD degree in electrical and computer engineering from Columbia University, New York, NY. She is currently an associate professor in the Department of Electrical and Computer Engineering, State University of New York at Stony Brook, Stony Brook, NY. Before joining Stony Brook, she was a member of Technical Staff in the area of mobile and wireless networking at Bell Labs Research, Lucent Technologies, NJ, and an assistant professor in the Department of Computer Science and Engineering, State University of New York at Buffalo, Buffalo, NY. Her research interests include algorithm and protocol design in wireless networks and communications, mobile and distributed computing, as well as networked sensing and detection. She has served in executive committee and technical committee of numerous conferences and funding review panels, and served as the associate editor of IEEE Transactions on Mobile Computing. She achieved the US National Science Foundation (NSF) career award in 2005, and ONR challenge award in 2010. She is a member of the IEEE.

Guangxue Yue received his M.S. and Ph.D. degrees in Computer Science and Technology from Hunan University, Changsha, China, in 2004, and 2012, respectively. He is currently Professor with the College of Mathematics, Physics and Information Engineering, Jiaxing University, Jiaxing, China. His main research interests include distributed computing & network, network security. In these areas, he has published more than 30 technical papers in journals. Dr. Yue served as Technical Program Committee Chair in various international IEEE conferences, such as BIC-TA2010, IITS2010, ISECS2010, ISECS2008, ISIP2009, ISECS2009 and ISISE2008.

Shigen Shen received the B.S. degree in fundamental mathematics from Zhejiang Normal University, Jinhua, China, in 1995, the M.S. degree in computer science and technology from Zhejiang University, Hangzhou, China, in 2005, and the Ph.D. degree in pattern recognition and intelligent systems from Donghua University, Shanghai, China, in 2013. He is currently a Professor with the Department of Computer Science and Engineering, Shaoxing University, Shaoxing, China. He is also with the College of Mathematics, Physics and Information Engineering, Jiaxing University, Jiaxing, China. His current research interests include wireless sensor networks, cloud computing and game theory.