Performance analysis of Evolutionary Game Theory-Based Information Dissemination Schemes

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Abstract

In vehicular networks, usually information is disseminated thanks to the cooperation between node pairs. In this article, we investigate a mechanism that encourages a sufficient number of vehicles to cooperate in order to effectively disseminate information in a vehicular ad hoc network (VANET). We consider the scenario that most of traffic (such as traffic jamming status, online movies, and online music) is broadcasted. Each node (vehicle) can choose one of two strategies: cooperation (forwarding) or defection (dropping), and may change its strategy period by period. By following the cooperation strategy, a node helps to disseminate information through the network, but consumes its own bandwidth. A node following the defection strategy simply receives information without any cost. Nevertheless, when all nodes select the defection strategy, the system is trapped into a prisoner dilemma situation such that no one can receive information. In this article, we model the cooperation/defection behavior of each node via the evolutionary game theory (EGT), such that each node targets to achieve a high information dissemination rate, and low bandwidth consumption, so as to save its resources. Then, we design an EGT-based information dissemination scheme (EGID), that can be applied to any existing data dissemination schemes. We establish an analytical model to characterize the performance of the EGID scheme and study its property in evolutionary stable states.

Index Terms

Evolutionary game theory, vehicular networks, information dissemination, cooperation

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I. INTRODUCTION

Communication between vehicles become more and more important nowadays to improve the user experience in driving and riding. Usually, information or data is disseminated between vehicles to support safety application, traffic monitoring and management applications, and infotament applications. More recently, exchanging information offloaded from vehicles that have access to other networks (cellular networks, WLANs) also becomes an important use case. To disseminate information/data over the vehicle ad hoc networks (VANETs) requires the cooperation between vehicles. When too many nodes participate in cooperation, the network may become congested due to too many duplicate transmissions. In the literature, this is referred to as the broadcast storm problem [1]. To solve such a problem, many information dissemination protocols are thus proposed (as surveyed in [2]), to improve information dissemination rate. Nevertheless, the understanding of how vehicles cooperate in vehicular ad hoc networks (VANET) for information dissemination from a theoretical point of view is still not clear, as indicated in [2], and needs further deep investigation.

There is a rich literature to study the forwarding/routing problem in wireless networks via classical game theory [3], [4], [5], [6]. Nodes select their strategies of cooperation or defection so as to maximize their payoff, according to the strategies of their neighbors. However, for a large scale dynamic system, finding the strategies that maxmin every players's payoff is difficult and sometimes infeasible.

The goal of this article is to find answers to the following problem: *Is it possible to design a mechanism that dynamically adjusts the number of cooperators in the VANET, so as to optimize system performance, which is adaptive to network topology, traffic load and various information dissemination schemes?* To the best of our knowledge, there is no literature in such an aspect yet.

We use Evolutionary Game Theory (EGT)([7]) to design such a mechanism. In the classical game theory, determining one player's strategy needs to know all other players' strategies, which is not adapted to the highly dynamic VANET content. In contrast, in EGT, less knowledge is required. Any player can periodically change its strategy, which only depends on the knowledge of its strategy and fitness, and its randomly encountered player's strategy and fitness. The fitness of a player is evaluated by how well its strategy plays in the system. Such features of EGT leads to less message exchange and computation, which fits the VANET environment. Based on EGT, we design a generalized information dissemination scheme, called EGID (Evolutionary Game theory based Information Dissemination scheme). It contains one *cooperator selection module* to adaptively select cooperators, guided by the EGT, and one *information* *dissemination module* that can apply different information dissemination schemes. The cooperator selection module is designed according to the performance requirements of the system. As a typical example, we consider high information dissemination rate (to disseminate more information) and low bandwidth consumption (to reserve resources for future use).

The rest of the article is organized as follows. In Section II, we review related work on information dissemination in VANETs, and evolutionary game theory. We propose our evolutionary game theory based information dissemination scheme in Section III. After that we model and analyze its performances in Section IV. Finally we conclude the paper in Section V.

II. Related work

A. *Information dissemination in vehicular networks*

The flooding scheme is known to be inefficient for the information dissemination in VANETs due to the well-known broadcast storm problem [1]. When there are too many cooperators, the network is over-congested due to too many redundant transmissions. Reducing the number of disseminated packets in time, spatial, or message domain solves the above problem. The solution in the time domain is to increase the broadcasting time interval ([8], [9], [10]). In spatial domain we can limit the number of forwarders ([11], [12], [13] , [14], [15]), or the rebroadcasting probability ([16], [17], [18], [19]). In the message domain we use information aggregation (TrafficInfo [20]), or discard unrelated information (TrafficView [21]).

In general, information dissemination schemes can be classified into two main categories: distance-aware and distance-independent. The schemes in the first category used GPS and digital map of roads to get the distance between neighbors to determine the next hop. The latter schemes only used local knowledge, such as local broadcast probability, node density, and information delivery history of neighbors.

One common strategy in all distance-aware information dissemination schemes is to give the furthest node in the neighborhood the highest priority to deliver the information. The idea is to make the largest progress in the distance for the information dissemination. UMB [22] proposed to use the handshake between the sender and potential forwarders to decide the next hop forwarder. The source node sends a request-to-broadcast (RTB), then all its neighbors in turn wait for a certain time and return a clear-to-broadcast (CTB) back to the source node. The larger the distance between the source and the neighbor is, the later the neighbor replies with the CTB. Then the source selects the neighbor that is the last to reply to forward the information. Smart Broadcast [23] improved UMB by letting the furthest node reply first, which reduced the delay. EDT [12] proposed that after receiving a new packet, each node needs to wait for $(1 - D/TR) * maxWT$ time before it can forward the packet. Here D is the distance between the sender and receiver, TR is the transmission range, and $maxWT$ is the maximal waiting time. In addition, packets can only be forwarded in the opposite direction. The p-persistent and 1-persistent broadcasting schemes are investigated in [16]. The furthest node should have higher probability to broadcast a packet (p-persistent) or be assigned a smaller slot for broadcasting (1-persistent). Both distance and local node density are taken into consideration to compute rebroadcast probability in Irresponsible Forwarding scheme [19]. Each node rebroadcasts a packet with a probability $\exp(-\rho_s(z-d)/c)$, where ρ_s is the local node density, z is the transmission range, d is the distance between the sender and the receiver, and $c \geq 1$ is a shaping parameter. Intuitively, a receiver that is further away from the sender with less neighboring nodes has a higher probability to rebroadcast the packet. To avoid loops, in all of the above schemes, a node does not rebroadcast the packet if it hears at least two copies of the same packet.

Distance-independent information dissemination (or packet forwarding) problem is extensively studied in ad hoc networks, and sensor networks. In [4], [5], [6], the cooperation behavior for wireless nodes is studied via a repeated game. In [4], the payoff function $u(s) = \alpha(s) + \beta(s)$ is proposed for the general information dissemination problem , where $\alpha(s)$ is the reward for the strategy s and $\beta(s)$ is the cost for using s. In [5], the authors considered the payoff matrix such that a node receives a reward α when its packet is forwarded, gets a punishment $-\alpha$ when the packet is not forwarded, and consumes a cost -1 in forwarding one packet for others. It was shown that the generous tit-for-tat strategy leads to the Nash equilibrium (NE). Contrarily to scenarios in [4], [5], in which traffic type is unicast, the paper [6] studied broadcast packet forwarding in multi-hop wireless networks. It has been shown that when the forwarding probability is $p = 1-(C/G)^{1/(n-1)}$, where C is the transmission cost, G is the successful forwarding gain, and n is the number of neighbors of the originator of the packet, the network reaches a mixed strategy NE. Nevertheless, such schemes based on classical game theory may not be applicable for VANET as it is hard to guarantee that each player in the game is rational. Here rational means that the player selects the strategy that maxmizes its payoff. Gossip-based scheme [24] is the simplest information dissemination scheme that does not rely on the knowledge of location of nodes. Each node rebroadcasts the received packet with a fixed probability.

B. *Brief introduction to evolutionary game theory (EGT)*

Inspired by the evolution of different species in biology, evolutionary game theory studies the dynamic of populations as a result of the interaction between different species. Under the framework of the evolutionary game, a species with a higher fitness (estimated by the mean payoff between this species and all players) fits the system better by producing more replicas. Compared with the classical game theory, the evolutionary game theory has two advantages: no requirement on rationality, and capability to handle large scale systems.

The Evolutionary Stable State (ESS) is a key concept in EGT, similar to the concept of the Nash Equilibrium in the classical game theory. A state of strategies, i.e., a distribution of population of species with different strategies, is said to be evolutionary stable, if no mutant strategy can invade. Consider a game where each player can play a strategy from $s_1, s_2, \ldots, s_k$. Let y_i denote the percentage of players with strategy s_i. If $y^\star = (y_1^\star, y_2^\star, \ldots, y_k^\star)$ is an ESS, it means that a system in a state disturbed from $y^\star$ a little bit will iteratively return back to $y^\star$. In another word, when a system is in an ESS, the number of population in different species maintains at a stable level. Comparing with the NE in the classical game theory, the ESS is more restrictive compared with the (weak) NE but less restrictive compared with the strict NE.

Due to its simple and effectiveness, this framework of EGT has a wide range of applications, such as in channel access [25], power control [25], network formation [26], dynamic routing [27], and cognitive radio networks [28].

III. Evolutionary game theory based information dissemination scheme

A. *System configuration*

Consider a multi-hop VANET with n vehicles (nodes). The connectivity graph of the network is based on the distance between node pairs, which may change over time. Nodes compete for the channel access using CSMA mechanism. Information are disseminated (broadcasted) over the whole network from several seed nodes through multi-hop transmissions. Each node can adopt one of two strategies at each moment: cooperation (forwarding), or defection (dropping). The cooperator benefits its one-hop neighbors by broadcasting information, and consumes its bandwidth. The defector receives information from its neighboring cooperators, and then reserves its bandwidth for its own future usage. The time is divided into sequential periods, $T_1, T_2, \ldots, T_j, \ldots$. Each period contains τ time slots such that one time slot is equal to the time needed to disseminate one piece of information. Within a period T_j, each node remains its strategy unchanged. Each node may change its strategy at the end of each period. We assume that broadcasted information of the same size. In the rest of paper, we will use information/packets interchangeably for simplicity of description. We consider that the buffer for information is sufficiently large, so that each node stores each piece of received information unless it is redundant.

*B. **EGID scheme***

In this section, we present our evolutionary game theory based information dissemination (EGID) scheme. As illustrated in Fig. 1, this scheme includes two modules: *cooperator selection module*, and *information dissemination module*. The cooperator selection module controls the number of cooperators in the network so as to guarantee system performance, while the information dissemination module applies various existing schemes. The information dissemination module provides the knowledge of amount of transmitted/received information to the cooperator selection module to assist the adaptation of the number of cooperators in the network. On the other hand, the cooperator selection module provides the decision of whether to cooperate to the information dissemination module. The goal of these two modules working together is to disseminate more information with less bandwidth consumption.

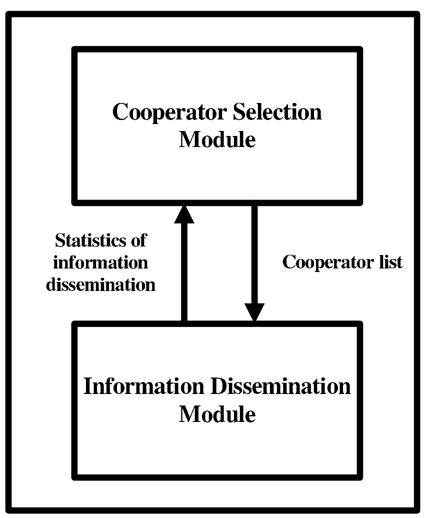

Fig. 1. The composition of the EGID scheme

*1) **Cooperator selection module**:* In our definition, the cooperators are nodes that may forward information for others. This does not mean that cooperators forward every piece of information they received, as this also depends on the information dissemination module. The defectors are nodes that always refuse to forward information. In each node, the cooperator selection module determines the node's strategy in a evolutionary game manner. Each node adjusts its strategy periodically according to its fitness (payoff with its neighbors). Consider the game played by any node x in the set of vehicles V and its one-hop neighbors in the set N_x. Let $\Pi_x(T_j)$ be the payoff (utility) of this node x during the period T_j. We design the payoff based on these two principles: 1) a node x that contributes more in the information dissemination has a higher payoff, 2) a node x that consumes less bandwidth in the broadcasting has a higher payoff. Then the payoff is constructed by two parts: the contribution to the information dissemination in the cluster including the node x and its one-hop neighbors, denoted as $\alpha_x(T_j)$, and the cost in the bandwidth consumption, denoted as $-\beta_x(T_j)$. Thus in total, $\Pi_x(T_j)$ can be expressed as

$$\Pi_x(T_j) \;\; = \;\; \alpha_x(T_j) - \beta_x(T_j). \tag{1}$$

We consider that the reward to the contribution in the information dissemination, $\alpha_x(T)$, is proportional to the amount of disseminated information related to the node x in the period T_j, $\mu_x(T_j)$, and a synergy factor r, i.e.,

$$\alpha_x(T_j) = \mu_x(T_j) r. \tag{2}$$

The synergy factor controls the tradeoff between the information dissemination rate and the bandwidth consumption. The larger r is, the amount of disseminated information is more important compared with the bandwidth consumption. Therefore, intuitively, a larger r encourages more cooperation, and a smaller r encourages more defection. The amount of disseminated information with the node x in the period T_j, $\mu_x(T_j)$ can be expressed as the sum of two terms, i.e.,

$$\mu_x(T_j) = \mu_x^{out}(T_j) + \mu_x^{in}(T_j), \tag{3}$$

which are amount of the information disseminated from the node x to its one-hop neighbors, and amount of information received at the node x from its one-neighbors respectively. Only considering information disseminated to the node x is not sufficient, as that will lead to a payoff function that always favors defectors. Since duplicated information does not add more benefit, we only consider the information that arrives at each node for the first time. In practice, $\mu_x^{in}(T_j)$ can be measured locally, while $\mu_x^{out}(T_j)$ can be estimated according to the feedback from x's neighbors.

The bandwidth consumption of a node x in the period T_j, $\beta_x(T_j)$, is defined as the amount of information broadcasted from the node x in this period, which is proportional to the number of packets broadcasted

OnReceiveInformation(f)
{
if Information f is not redundant **then**
  $src \leftarrow f.source$;
  $e^{in}++$;
  if $src \notin NbSet$ **then**
    $NbSet \leftarrow NbSet \bigcup \{src\}$;
    $e^{in}_{src} \leftarrow 1$;
  else
    $e^{in}_{src}++$;
  end if
end if
}
OnBroadcastInformation(f)
{
$e^{out}++$;
}
OnStartofPeriod()
{
$e^{in} \leftarrow 0$;
$e^{out} \leftarrow 0$;
$NbSet \leftarrow \emptyset$;
Timer(EndOfPeriod,τ);
}
OnEndtofPeriod()
{
Sends e^{in}_{v} to all recorded neighbors v such that $v \in NbSet$;
Collects $e^{in}_{i}(v)$ from all neighbors $v \in N_i$;
$\mu^{in}_{i}(T_j) \leftarrow e^{in}$;
$\mu^{out}_{i}(T_j) \leftarrow \sum_{v \in N_i} e^{in}_{i}(v)$;
$\alpha_i(T_j) \leftarrow r(\mu^{in}_{i}(T_j) + \mu^{out}_{i}(T_j))$;
$\beta_i(T_j) \leftarrow e^{out}$;
$\Pi_i(T_j) \leftarrow \alpha_i(T_j) - \beta_i(T_j)$;
Randomly selects an one-hop neighbor j of the node i and get its payoff $\Pi_j(T)$;
Computes strategy adoption probability $P_{s_i \to s_h} = \frac{1}{1+\exp[(\Pi_i(T_j)-\Pi_h(T_j))/\kappa]}$;
Draws a random number ω;
if $\omega \leq P_{s_i \to s_h}$ **then**
  $s_i \leftarrow s_h$;
end if
Timer(StartOfPeriod,1);
}

Fig. 2. Strategy evolution process at any node i in the period T_j

by the node x.

The evolution of strategies for the node i within a period T_j works as follows (shown in Fig. 2). At the start of this period, the node i resets the amount of information sent to/from other nodes to zero, and clears the set of neighboring cooperators $Nbset$. Within this period, every time that a piece of non-redundant information f is received, the counter for the disseminated information to the node i, e^{in} increases by 1 (or generally the amount of information contained in the packet). When the source of the information f is not recorded in $NbSet$, $Nbset$ is updated by including this neighbor, and the counter for the disseminated information from this source src to the node i, e^{in}_{src} is set as 1; otherwise e^{in}_{src} increases by 1. Within this period, every time that a piece of information is disseminated from the node i, the counter for disseminated information from the node i, e^{out} increases by 1. At the end of this period, the node i sends packets of values e^{in}_{v} to all its neighboring cooperators, such that $v \in Nbset$. e^{in}_{v} from node i indicates the amount of information disseminated from node v to the node i. This packet can be transmitted via a separate channel, or in the preassigned time slots. Then the node i waits and collects all $e^{in}_{i}(v)$ from neighbors $v \in N_i$. N_i is the neighbor set of the node i, which can be constructed by the exchange of hello messages. Then the node i computes its payoff according to eq. (1), eq. (2), eq. (3). Let s_x be a binary variable that indicates the node x's strategy. When the node x is a cooperator, $s_x = 1$, otherwise $s_x = 0$. Then the node i revises its strategy according to a randomly selected one-hop neighbor h. The probability that the node i mimics (adopts) the node h's strategy is

$$P_{s_i \to s_h} = \frac{1}{1 + \exp[(\Pi_i(T_j) - \Pi_h(T_j))/\kappa]}, \tag{4}$$

where κ quantifies the uncertainty by strategy adoption. Such a rule is usually referred to as the logit rule in the literature of game theory [29], [30]. The rationality is that, when the node h has a higher payoff than that of the node i, the node i should learn the node h's strategy with a probability larger than 1/2, and the larger difference is, the larger probability is; when the node j's payoff is less than the node i, the node i is less likely to adopt the node h's strategy, i.e., $P_{s_i \to s_h} < 1/2$. When κ is larger, the updating of strategies is more random; when κ is smaller, it is more deterministic. For example, in case that $\Pi_i(T_j) = 0.05$ and $\Pi_h(T_j) = 0.1$, the strategy adoption probability $P_{s_i \to s_h}$ is 0.99, 0.62, 0.51 when κ is 0.01, 0.1, 1 respectively. After the node i determines its strategy at the end of the period, the node i triggers the timer to restart a new period.

2) ***Information dissemination module****:* In the framework of EGID, each cooperator x competes for the channel access with a pre-given probability λ_x for each time slot. λ_x can also be regarded as the traffic sending rate of the node x, while the unit is packets per time slot.

Various information dissemination schemes can be put inside the information dissemination module of EGID. For example, the distance-aware $p-persistent$ scheme ([16]) can be directly applied. Two features are commonly suggested to avoid unnecessary redundant transmissions. The first one, *broadcast cancelation*, is that, for each forwarder, if it senses packets have already been transmitted by one of its neighbors (other than the originator), it withdraws the ongoing broadcasting. The second one, *furthest node forward first*, is usually based on the first feature. The node that is further to the originator of the broadcasting information has a higher probability to broadcast the information first. In EGID scheme, this can be enabled by letting any node i accesses the channel with a probability λ_i when the information is generated by itself, and accesses the channel with a probability $\gamma\frac{dist(i,j)}{R}\lambda_i$, to forward a piece of information that is previously received from the the node j, where $dist(i,j)$ denote the distance between these two nodes, and R is the transmission range. The distance between nodes pair i and j can be measured as Euclidean distance according to GPS, or other metrics.

IV. Performance modelling of the EGID scheme

In this section, we establish a model for the EGID scheme, to understand i) whether cooperation ratio (percentage of cooperators) converges, ii) how fast the cooperation ratio converges, iii) how cooperation incentive is influenced by different system parameters, iv) how information dissemination module affects the performance of EGID. For simplicity, we first investigate the flooding as the information dissemination scheme of EGID. We model disseminated information from/to each node, and the bandwidth consumption in Section IV-A. We model the distribution of payoff function, and analyze the system dynamics in Section IV-B. We prove the ESS property of the system when there is infinity information or limited information to be disseminated in Section IV-C. We present the model to predict information dissemination rate, and the bandwidth consumption in Section IV-D. All involved variables are listed in Table I.

*A. **Amount of disseminated information and bandwidth consumption***

We start with the modelling for calculation of the amount of disseminated information and bandwidth consumption. First of all, we derive the model for any node v, then we extend the model to analyze the average case.

*1) **Model for any node**:* The disseminated information's amount is related to the following factors, i) how fast each node sends out information, ii) the probability that a piece of information is successfully received by a node without collision, iii) the probability that the information received is not redundant (not previously received). The first factor is related to the channel access probability λ_x of any node x.

Variable	Meaning
System parameters	
T_j	The j's time period in the sequence
τ	Number of slots in one period
s_i	Indicator of strategy adopted by the node i (0 for defector, and 1 for cooperator)
n	Number of nodes in the network
m	Number of seed nodes (source of information) in the network
N_x	Set of neighbors of the node x
λ_x	Channel access probability of the node x
$\overline{\lambda}$	Mean channel access probability
k	Mean node degree
γ	Parameter to adjust the channel accessing probability for *furthest node forward first* scheme
Variables for computing payoff	
$\Pi_x(T_j)$	Payoff for the node x in the period T_j (referred as to eq. (1))
$\alpha_x(T_j)$	Information dissemination related to the node x in the period T_j
$\beta_x(T_j)$	Information dissemination's cost with the node x in the period T_j
$\mu_x(T_j)$	Sum of the amount of disseminated information to/from the node x in the period T_j
$\mu_x^{out}(T_j)$	Amount of disseminated information from the node x in the period T_j
$\mu_x^{in}(T_j)$	Amount of disseminated information to the node x in the period T_j
r	Synergy factor in eq. (2)
$P_{s_i \to s_h}$	Probability that the node i adopts the node h's strategy in eq. (4)
κ	Parameter to adjust the strategy adoption probability in eq. (4)
Variables for analysis of the dynamics of the system	
$q_{v \to j}$	Probability that a piece of information from the node v to j is received successfully
$p_i(T_j)$	Probability that a received packet is not redundant at the node i in the period T_j
$p(\Theta, T_j)$	Mean of $p_i(T_j)$ in the period T_j when the cooperation ratio is Θ
I	Amount of information to be disseminated into the network
$I^\star$	Maximal amount of information which can be received by each node in the network
$I_i(T_j)$	Amount of information received by the node i before the period T_j
$I(T_j)$	Mean of the amount of information received by each node before the period T_j
z_i	Indicator of whether the node i is a seed node (1 for seed node, and 0 for others)
Θ	Cooperation ratio (percentage of cooperators) of the network
$\xi(\Theta)$	Probability of the occurrence of *stable defectors*
ϵ	Parameter to shape the relationship between $\xi(\Theta)$ and Θ
Θ^+	Cooperation ratio of the network removing all *stable defectors*
$q(\Theta)$	Mean value of all $q_{i \to j}$ when the cooperation ratio is Θ
$\overline{\mu_c^{out}(\Theta, T_j)}$	Mean of $\mu_x^{out}(T_j)$ when the cooperation ratio is Θ
$\overline{\mu_c^{in}(\Theta, T_j)}$	Mean of $\mu_x^{in}(T_j)$ for a cooperator when the cooperation ratio is Θ
$\overline{\mu_d^{in}(\Theta, T_j)}$	Mean of $\mu_x^{in}(T_j)$ for a defector when the cooperation ratio is Θ
$\pi^x(\Theta, T_j)$	Payoff of a cooperator/defector ($x = c/d$) in the period T_j with a cooperation ratio Θ
$\overline{\pi^x(\Theta, T_j)}$	Mean of $\pi^x(\Theta, T_j)$, $x = \{c, d\}$
$\sigma(\pi^x(\Theta, T_j))$	Standard deviation of $\pi^x(\Theta, T_j)$, $x = \{c, d\}$
$\overline{\mu_{all}(\Theta, T_j)}$	Total amount of disseminated information in the period T_j with a cooperation ratio Θ

TABLE I
VARIABLES FOR THE PERFORMANCE MODELLING OF THE EGID SCHEME

For the rest of three factors, we denote $q_{v\to x}$ as the probability that a piece of information from the node v to the node x is received successfully, and denote $p_x(T_j)$ as the probability that a received packet at the node x is not redundant in the period T_j. Intuitively, on average, each neighbor y of a cooperator x receives $q_{x\to y}p_y(T_j)\lambda_x\tau$ pieces of information from x's broadcast during the period T_j.

Consequentially, in the period T_j, the total amount of information disseminated from a node x to all its neighbors is

$$\mu_x^{out}(T_j) = \tau\lambda_x s_x \sum_{v\in N_x} q_{x\to v}p_v(T_j), \tag{5}$$

the total amount of information disseminated to the node x is

$$\mu_x^{in}(T_j) = \sum_{v\in N_x, s_v=1} \tau\lambda_v q_{v\to x}p_x(T_j), \tag{6}$$

and the bandwidth consumption for the node x can straightforwardly modelled as

$$\beta_x(T) = \tau\lambda_x s_x. \tag{7}$$

The successful packet delivery probability $q_{v\to i}$ can be modelled as

$$q_{v\to i} = \prod_{u\in N_i \bigcup\{i\}-\{v\}, s_u=1} (1-\lambda_u). \tag{8}$$

The detail of derivation is given in Appendix A.

The probability that a received packet at the node i is not redundant decreases as the amount of received information increases. So we define it as a function of the period T_j. It can be modelled as

$$p_i(T_j) = (1 - I_i(T_j)/I)\frac{1}{\sum_{v\in N_i, s_v=1} q_{v\to i} + z_i}, \tag{9}$$

Here $I_i(T_j)$ is the amount of stored information at the node i at the start of a period T_j, I is the total amount of information to be disseminated, and z_i is an indicator for whether the node i is a seed node. z_i equals 1 when the node i is a seed node, and it is zero otherwise. The detail of the derivation is given in Appendix B.

*2) **Model of the mean information dissemination rate and bandwidth consumption**:* Based on the analysis for the per node performance, we extend the analysis to the average case. We study the information dissemination amount from/to a cooperator/defector, and the bandwidth consumption of a cooperator, when it is surrounded with mean number of cooperators and defectors. For the ease of analysis, we focus on the network without *stable defectors*. We define a *stable defector* as the defector that is surrounded with defectors. It does not have the chance to become a cooperator at the end of a period, according to the strategy evolution policy in Section III-B1. The amount of disseminated information from/to a *stable defector*, and the bandwidth consumption by a *stable defector* are always zero. Therefore, we treat it specially. Given the cooperation ratio (the percentage of cooperators) Θ in the original network, the probability of the occurrence of *stable defectors* can be approximated as

$$\xi(\Theta) = \sum_{i=1}^{n} P_d(i)(1-\Theta_d(i))^{i+1}, \tag{10}$$

where $P_d(i)$ is the probability that a node's degree is i, and $\Theta_d(i)$ is the mean cooperation ratio for neighbors of a defector of degree i. The cooperation ratio of the network removing all *stable defectors* is

$$\Theta^+ = \Theta/(1-\xi(\Theta)). \tag{11}$$

The mean value of the successful packet delivery probability $q(\Theta)$, and the probability that received information is not redundant $p(\Theta, T_j)$ in a network with a cooperation ratio Θ in the period T_j can be derived as follows. Let k denote the mean node degree. The set of neighboring cooperators is $k\Theta^+$ on average. On average the size of the set of nodes that may collide a transmission from a sender j to a receiver i, i.e. $\{v \in N_i \bigcup\{i\} - \{j\}, s_v = 1\}$ in eq. ((8)), is equal to the product of k and the cooperation ratio Θ^+. Let $\overline{\lambda}$ denote the mean channel access probability (sending rate in the unit of packets/time slot) of nodes in the system, the average successful packet delivery probability can be approximated by

$$q(\Theta) = \left(1-\overline{\lambda}\right)^{k\Theta^+}. \tag{12}$$

Let m denote the number of seed nodes, i.e., nodes that are the sources of information. According to eq. (9), the mean probability that received information is not redundant in the period T_j, $p(\Theta, T_j)$, equals to

$$\begin{aligned} p(\Theta, T_j) &= (1 - I_i(T_j)/I)\frac{1}{q(\Theta)k\Theta^+ + m/n} \\ &= (1 - I_i(T_j)/I)\frac{1}{\left(1-\overline{\lambda}\right)^{k\Theta^+} k\Theta^+ + m/n} \end{aligned} \tag{13}$$

Based on eq.s (12),(13), (5), the mean value of total amount of information disseminated from a cooperator in the period T_j is

$$\begin{aligned}\overline{\mu_c^{out}(\Theta, T_j)} &= \tau\overline{\lambda}kq(\Theta)p(\Theta, T_j) \\ &= \tau\overline{\lambda}(1 - I_i(T_j)/I)\frac{\left(1-\overline{\lambda}\right)^{k\Theta^+}k}{\left(1-\overline{\lambda}\right)^{k\Theta^+}k\Theta^+ + m/n}. \end{aligned} \quad (14)$$

Based on eq.s (12),(13), (6), the mean value of total amount of information disseminated to a cooperator c in the period T_j is

$$\begin{aligned}\overline{\mu_c^{in}(\Theta, T_j)} &= \tau\overline{\lambda}k\Theta^+ q(\Theta)p(\Theta, T_j) \\ &= \tau\overline{\lambda}\frac{\left(1-\overline{\lambda}\right)^{k\Theta^+}k\Theta^+}{\left(1-\overline{\lambda}\right)^{k\Theta^+}k\Theta^+ + m/n}(1 - I_i(T_j)/I). \end{aligned} \quad (15)$$

Considering that there are two kinds of defectors: defectors that are adjacent to at least one cooperator, and *stable defectors*. The mean value of total amount of information disseminated to a defectors d in the period T_j is the weighted mean of these two kinds of defectors. Notice that the number of the former defectors is $n(1-\Theta-\xi(\Theta))$, and the number of the latter defectors is $n\xi(\Theta)$. The number of information received at each defector in the period T_j is on average

$$\begin{aligned}\overline{\mu_d^{in}(\Theta, T_j)} &= \tau\overline{\lambda}k\Theta^+ q(\Theta)p(\Theta, T_j)\frac{1-\Theta-\xi(\Theta)}{1-\Theta} \\ &= \tau\overline{\lambda}\frac{\left(1-\overline{\lambda}\right)^{k\Theta^+}k\Theta^+}{\left(1-\overline{\lambda}\right)^{k\Theta^+}k\Theta^+ + m/n} \\ &\quad \frac{1-\Theta-\xi(\Theta)}{1-\Theta}(1 - I_i(T_j)/I). \end{aligned} \quad (16)$$

Straightforwardly, the mean value of bandwidth utilization by a cooperator in one period is

$$\overline{\beta} = \tau\overline{\lambda}. \quad (17)$$

B. ***Dynamics of the system***

In this subsection, we model the dynamics of the system, i.e., the variation of the cooperation ratio. We model the payoff of cooperators and defectors, according to the amount of disseminated information and bandwidth consumption derived in the last subsection. Then we model the variation of the cooperation ratio in one period.

We model the payoff of a cooperator(defector) in the period T_j in a network with a cooperation ratio

Θ as a random variable $\pi^c(\Theta, T_j)$ ($\pi^d(\Theta, T_j)$) that follows the normal distribution. Although such an approximation is heuristic, we will see later in the Section **??** that it matches well the simulation results. According to equations. (1), (2), (3), (14), (15), (16), (17)), we can model the mean payoff for a cooperator and a defector in the period T_j as

$$\begin{aligned} \overline{\pi^c(\Theta, T_j)} &= r\overline{\mu_c^{out}(\Theta, T_j)} + r\overline{\mu_c^{in}(\Theta, T_j)} - \tau\overline{\lambda} \\ \overline{\pi^d(\Theta, T_j)} &= r\overline{\mu_d^{in}(\Theta, T_j)}. \end{aligned} \tag{18}$$

We approximate the standard deviation of a cooperator or defector as

$$\begin{aligned} \sigma(\pi^c(\Theta, T_j)) &= \sigma(\tilde{\lambda})\overline{\pi^c(\Theta, T_j)} \\ \sigma(\pi^d(\Theta)) &= \sigma(\tilde{\lambda})\overline{\pi^d(\Theta, T_j)}, \end{aligned} \tag{19}$$

where $\tilde{\lambda} = \{\lambda_x | x \in N\}$.

The mean probability that a cooperator becomes a defector $P_{c\to d}(\Theta, T_j)$ can be approximated as

$$P_{c\to d}(\Theta, T_j) = E\left(\frac{1}{1 + \exp\left(\left(\pi^c(\Theta, T_j) - \pi^d(\Theta, T_j)\right)/\kappa\right)}\right). \tag{20}$$

The probability $P_{d\to c}(\Theta, T_j)$ can be estimated as $1 - P_{c\to d}(\Theta, T_j)$.

The dynamics of the system is as follows. At the end of the period T_j, there are $n\Theta$ cooperators and $n(1-\Theta)$ defectors. Each cooperator has a probability $1-\Theta$ to find a defector from its one-hop neighbors, and each defector has a probability Θ to find a cooperator from its one-hop neighbors. When a cooperator chooses a defector to mimic its strategy, it has the probability $P_{c\to d}(\Theta, T_j)$ to adopt the defector strategy. Similarly, when a defector chooses a cooperator to mimic its strategy, it has the probability $P_{d\to c}(\Theta, T_j)$ to adopt the cooperator strategy. Then on average, after one period T_j, there are

$$n(1-\Theta)\Theta P_{d\to c}(\Theta, T_j) \tag{21}$$

new cooperators, and

$$n\Theta(1-\Theta)P_{c\to d}(\Theta, T_j) \tag{22}$$

new defectors. Thus the variation of Θ is

$$\begin{aligned}\frac{d\Theta}{dt}(\Theta,T_j) &= -(1-\Theta)\Theta P_{c\to d}(\Theta,T_j)+(1-\Theta)\Theta P_{d\to c}(\Theta,T_j)\\ &= (1-\Theta)\Theta\left(1-2P_{c\to d}(\Theta,T_j)\right).\end{aligned} \tag{23}$$

C. *ESS property*

In this subsection, we discuss whether the system approaches evolutionary stable states (ESS), and what is the cooperation ratio when the system is in an ESS. We start with the case with infinity information to be disseminated (see Theorem 1), and then extend the analysis to the general case with limited amount of information to be disseminated (see Theorem 2).

Theorem 1: **Assuming that the network topology is fixed, when the number of information to be disseminated is infinity, the cooperation ratio Θ^* in an ESS for the n nodes with the EGID scheme on a flooding information dissemination scheme exists when $\Theta = 0$ and $r < \frac{1+m/n}{(k-1)}$, or $\Theta = 1$ and $r > \frac{k}{k-1}\frac{k+m/(nQ_2)}{k-m/(nQ_2)}$, or $0 < \Theta < 1$, and $P_{c\to d}(\Theta,T_j) = 1/2$. m is the number of seed nodes, k is the mean node degree, and $Q_2 = \left(1-\overline{\lambda}\right)^k$.**

The proof of Theorem 1 is given in the Appendix C.

Theorem 2: **Assuming that the network topology is fixed, when the number of information to be disseminated is finite, the ESS for the n nodes with the EGID scheme on a flooding information dissemination scheme exists when $\Theta = 0$ and $r < \frac{1+m/n}{(k-1)}\frac{1}{1-I^*/I}$, or $\Theta = 1$ and $r > \frac{k}{k-1}\frac{k+m/(nQ_2)}{k-m/(nQ_2)}\frac{1}{1-I^*/I}$. When $0 < \Theta < 1$, the cooperation ratio in the ESS, $\Theta^{-,*}$, is always less than Θ^* (see Theorem 1). Here I^* is maximal possible average amount of information disseminated to each node.**

The proof of Theorem 2 is given in the Appendix D.

Observations: The results from Theorems 1 and 2 leads to following observations, i) when there is a lot of information to be disseminated, the cooperation ratio remains at a level around $\Theta^\star$ for a long period (given that the network topology does not change too much); ii) when the information to be disseminated is burst, the cooperation ratio iteratively shrinks to a low level, as the probability that received information is redundant keeps increasing; iii) when information is periodically generated by seed nodes, the cooperation ratio periodically increases to a peak level then drops to a lower level.

D. *Information dissemination rate and consumed bandwidth*

In this section we model the information dissemination rate and the bandwidth consumption. According to the derivation of average information disseminated from each cooperator in eq. (14), we can see that, in the period T_j, on average $n\Theta\overline{\mu_c^{out}(\Theta, T_j)}$, i.e.,

$$\overline{\mu_{all}(\Theta, T_j)} = n\Theta\tau\overline{\lambda}\frac{\left(1-\overline{\lambda}\right)^{k\Theta^+} k}{\left(1-\overline{\lambda}\right)^{k\Theta^+} k\Theta^+ + m/n}(1 - I_i(T_j)/I) \tag{24}$$

non-duplicated pieces of information are disseminated through the network.

We consider the *network contention level* to characterize the bandwidth utilization, which is defined as

$$\min(\frac{1}{n}\sum_{x\in V}\sum_{v\in N_x\cup\{x\}, s_v=1}\lambda_v, 1) \tag{25}$$

This can be regarded as the mean occupied air time observed from each node. Since $\overline{\lambda} = \frac{1}{n}\sum_{x\in V}\lambda_x$, and the size of the set $\{v \in N_x \cup \{x\}\}$ is $(k+1)\Theta$ on average, the *network contention level* can be approximated as

$$\min(\Theta\overline{\lambda}(k+1), 1). \tag{26}$$

V. Conclusion

In this article, we use evolutionary game theory to study the cooperation behavior of vehicles in a VANET for information dissemination. We propose an information dissemination scheme, EGID, to adaptively adjust the number of cooperators in the network accordingly, so as to reduce the number of unnecessary transmissions. The EGID can apply existing information dissemination schemes to improve their performance further. We prove the property of the ESS for the EGID scheme when there are infinity or limited information to be disseminated.

Appendices

A. *Modelling of* $q_{v\to i}$

We consider that time is divided into slots. Each node randomly accesses the channel to send one piece of information in each slot. A piece of information (or a packet) is received successfully at the receiver, if this receiver does not try to access the channel at the same slot, and none of its one-hop neighbors try to access the channel at the same slot. The successful packet delivery probability is

$$q_{v\to i} = \prod_{u\in N_i\bigcup\{i\}-\{v\}, s_u=1}(1-\lambda_u).$$

B. *Modelling of* $p_i(T_j)$

The duplicated packets at node i can be received from the node i's neighboring cooperators, or can be obtained locally if this node is a seed node. For each unique packet, each node only forwards it once. When a node receives a packet for the second time, it discards it. The probability that a packet received in a period T_j is not redundant is equal to the product of two probabilities: $P1$ and $P2$. $P1$ is the probability that this packet has not been received in previous periods, and $P2$ is the probability that it is the first time that the node i receives this packet from its neighbors in this period.

The probability $P1$ is modelled as follows. Let $I_i(T_j)$ as the number of stored packets at the node i at the start of a period T_j, and I as the total number of packets to be received. Formally, $I_i(T_j) = \sum_{T_h \text{ is before } T_j} \mu_i^{in}(T_h)$. The probability that this information has not received by the node i in previous periods is $1 - I_i(T_j)/I$.

The probability $P2$ is modelled as follows. We consider that the network topology remains stable during one period. For a packet from a source s, assuming that it reaches the node i in f hops, then it can reach i's one-hop neighbors in $[f-1, f+1]$ hops. Therefore we assume that packets containing the same information reach the node i from i' neighbors in the same period. Each copy from the neighbor v is received by the node i successfully with a probability $q_{v\to i}w_{v\to i}$. Then in total, the number of copies of the same packet received at the node i in this period is equal to $\sum_{v\in N_i, s_v=1} w_{v\to i}q_{v\to i}$ plus z_i. z_i is an indicator of whether the node i is a seed node. It is 1 when the node i is a seed node, and 0 otherwise. Notice that, for the seed node, a piece of information is received locally only when it is broadcasted. So there exists the possibility that the first time that a piece of information is received at a seed node i is from its neighbor rather than node i itself. Then the second probability is equal to the inverse of the above number of copies.

Combining the above two probabilities together, we have

$$p_i(T_j) = (1 - I_i(T_j)/I)\frac{1}{\sum_{v\in N_i, s_v=1} w_{v\to i}q_{v\to i} + z_i}.$$

C. *Proof of Theorem 1*

Proof. When the number of packets to be disseminated is infinity, the ratio $I_i(T_j)/I$ is always 0. Therefore, for any node v, the term $(1 - I_v(T_j)/I)$ can be omitted in the calculation of the payoff. In addition, we omit the index T_j in such a case as $p_v(T_j)$ becomes time irrelevant.

According to the argument at the end of Section 3 in [31], when there are only two pure strategies, the ESS is equivalent to the stable equilibrium point.

We start with the trivial cases that $\Theta = 0$ or $\Theta = 1$. In both cases, $\frac{d\Theta}{dt} = 0$. However, whether these two states are ESSs depending on the setting of synergy factor r.

Considering the network in a state in which all nodes are defectors except one cooperators x, i.e. a state perturbed from state $\Theta = 0$. Since there is only one cooperator, the packet delivery probability q is always 1. The average number of copies of packets at x's one-hop neighbors is $1 + m/n$ on average. The payoff of the node x is

$$\Pi_x = r\tau\overline{\lambda}k\frac{1}{1+m/n} - \tau\overline{\lambda}, \tag{27}$$

and the payoff of any node v in its one-hop neighborhood is

$$\Pi_v = r\tau\overline{\lambda}\frac{1}{1+m/n}. \tag{28}$$

Denote $P^i_{c\to d}$, and $P^i_{d\to c}$ as the probability that a cooperator becomes a defector, or a defector becomes a cooperator in a system with i cooperators. Then at the end of period T_j, the probability that the node x becomes a defector is

$$\begin{aligned} P^0_{c\to d} &= \frac{1}{1+\exp\left(\left(\Pi_x - \Pi_v\right)/\kappa\right)} \\ &= \frac{1}{1+\exp\left(\left(\tau\overline{\lambda}\left(r(k-1)/(1+m/n)-1\right)\right)/\kappa\right)} \end{aligned} \tag{29}$$

After one period, the variation of the number of cooperators in the system is

$$-P^0_{c\to d} + k\left(1/k\right)P^0_{d\to c} = 1 - 2P^0_{c\to d} \tag{30}$$

When $r \geq \frac{1+m/n}{(k-1)}$, the variation is non-negative, meaning that the number of cooperators does not reduce to zero. Then the state $\Theta = 0$ is not a stable state in such a case. When $r < \frac{1+m/n}{(k-1)}$, the variation is negative. Then the state $\Theta = 0$ is a stable state and also an ESS.

Then we consider the network in a state in which all nodes are cooperators except one defector x, i.e. a state perturbed from state $\Theta = 1$. Define B_i as the set of nodes that are at i's hops away from the node x. We define Q_i as the packet delivery probability from the node x to the node v that at i's hops away , i.e., $Q_i = q_{u\to v}$, where u is a cooperator, and $v \in B_i$. Q_is can be modelled as follows:

$$Q_i = \begin{cases} \left(1-\overline{\lambda}\right)^{k-1}, & \text{if } i = 0, 1, \\ \left(1-\overline{\lambda}\right)^{k}, & \text{if } i \geq 2. \end{cases} \tag{31}$$

We define H_i as the number of copies of packets at the node v at i's hops away from x. H_i can be modelled as:

$$H_i = \begin{cases} kQ_0 + z_x, & \text{if } i = 0, \\ (k-1)Q_i + m/n, & \text{if } i = 1, \\ kQ_i + m/n, & \text{if } i \geq 2, \end{cases} \tag{32}$$

where z_x is a binary indicator whether x is a seed node or not.

The payoff of the defector x is

$$\Pi_x = r\tau\overline{\lambda}k\frac{Q_0}{H_0}, \tag{33}$$

and the payoff of any node v in x's one-hop neighborhood is

$$\begin{aligned} \Pi_v &= r\tau\overline{\lambda}(k-1)\frac{Q_1}{H_1} \\ &+ r\tau\overline{\lambda}\left(\frac{Q_0}{H_0} + \sum_{u\in N_v\cap B_1}\frac{Q_1}{H_1} + \sum_{u\in N_v\cap B_2}\frac{Q_2}{H_2}\right) \\ &- \tau\overline{\lambda}. \end{aligned} \tag{34}$$

After one period, the variation of the number of cooperators in the system is

$$-k\left(1/k\right)P^n_{c\to d} + P^n_{d\to c} = 1 - 2P^n_{c\to d}, \tag{35}$$

where

$$P^n_{c\to d} = \frac{1}{1+\exp\left(\left(\Pi_v(T_j) - \Pi_x(T_j)\right)/\kappa\right)}.$$

Notice that

$$Q_0/H_0 \leq 1/(k), \tag{36}$$

$$Q_1/H_1 \geq Q_2/H_2. \tag{37}$$

We can derive that

$$\Pi_v(T_j) - \Pi_x(T_j) \geq \tau\overline{\lambda}\left((k-1)r\left(2Q_2/H_2 - 1/(k)\right) - 1\right). \tag{38}$$

When

$$r > \frac{k}{k-1}\frac{k+m/(nQ_2)}{k-m/(nQ_2)}, \tag{39}$$

$\Pi_v(T_j) - \Pi_x(T_j) > 0$, i.e., $1 - 2P^n_{c\to d} > 0$, meaning the number of cooperator will increase. In such a case, the state $\Theta = 1$ is a stable state and an ESS.

Next we show that, the point $0 < \Theta^\star < 1$ such that $P_{c\to d}(\Theta^\star, T_j) = 1/2$ is another stable equilibrium point. First of all, $\frac{d\Theta^\star}{dt} = 0$, when $P_{c\to d}(\Theta^\star, T_j) = 1/2$. Recall the modelling of $P_{c\to d}(\Theta, T_j)$ in eq. (20), (14) (16) (15) (18) (19), we observe that $P_{c\to d}(\Theta, T_j)$ is an increasing function of Θ. When $1 > \Theta > \Theta^\star$, $P_{c\to d}(\Theta, T_j) > P_{c\to d}(\Theta^\star, T_j) = 1/2$. Therefore the cooperation ratio iteratively reduces to $\Theta^\star$. Similarly, when $0 < \Theta < \Theta^\star$, $P_{c\to d}(\Theta, T_j) < P_{c\to d}(\Theta^\star, T_j) = 1/2$. The cooperation ratio iteratively increases to $\Theta^\star$. $\square$

D. ***Proof of Theorem 2***

Proof. The proof is similar to that for Theorem 1, except that $I_i(T_j)/I$ is not zero, and cannot be omitted.

Let I^* be the upper bound of the average number of packets disseminated to each node. I^* is not necessary 1, as the network may be disconnected, and there exists packet loss.

When $\Theta = 0$, similar to eq. (27), eq. (28), and eq. (30) in Theorem 1, at the end of period T_j, the probability that a node x becomes a defector approaches

$$\begin{aligned} P^0_{c\to d}(T_j) &= \frac{1}{1+\exp\left(\left(\Pi_x(T_j) - \Pi_v(T_j)\right)/\kappa\right)} \\ &= \frac{1}{1+\exp\left(\left(\tau\overline{\lambda}\left(r(k-1)/(1+m/n)(1-I^*/I) - 1\right)\right)/\kappa\right)} \end{aligned} \tag{40}$$

Then we can observe that, when $r < \frac{1+m/n}{(k-1)}\frac{1}{1-I^*/I}$, the variation of the number of cooperators in the system, $-P^0_{c\to d}(T_j) + k\,(1/k)\,P^0_{d\to c} = 1 - 2P^0_{c\to d}(T_j)$ is negative. Then in such a case, $\Theta = 0$ is a stable state and an ESS.

When $\Theta = 1$, we can follow similar steps from eq. (31) to (38). Then we have

$$\Pi_v(T_j) - \Pi_x(T_j) \geq \tau\overline{\lambda}\left((k-1)r\left(2Q_2/H_2 - 1/(k)\right)(1 - I^*/I) - 1\right). \tag{41}$$

When

$$r > \frac{k}{k-1}\frac{k+m/(nQ_2)}{k-m/(nQ_2)}\frac{1}{1-I^*/I}, \tag{42}$$

$\Pi_v(T_j) - \Pi_x(T_j) > 0$, meaning the number of cooperator will increase. In such a case, the state $\Theta = 1$ is a stable state and an ESS.

When $0 < \Theta < 1$, let $\mu_{c,\infty}^{out}(\Theta)$, $\mu_{c,\infty}^{out}(\Theta)$, and $\mu_{d,\infty}^{in}(\Theta)$ denote the amount of disseminated information when there is infinity information to be disseminated. Let $\pi^{c,\infty}(\Theta)$ and $\pi^{d,\infty}(\Theta)$ denote the payoff for a cooperator or defector when the information dissemination amount is infinity. Then we have, in general, the difference of a cooperator and a defector when there are limited number of packets to be disseminated iteratively approaches

$$\pi^c(\Theta, T_j) - \pi^d(\Theta, T_j) = r(\mu_{c,\infty}^{in}(\Theta) + \mu_{c,\infty}^{out}(\Theta) - \mu_{d,\infty}^{in}(\Theta))(1 - I^*/I) - \tau\overline{\lambda} < \pi^{c,\infty}(\Theta) - \pi^{d,\infty}(\Theta). \tag{43}$$

Then in general,

$$\begin{aligned} P_{c\to d}(\Theta^*, T_j) &= E\left(\frac{1}{1+\exp\left(\left(\pi^c(\Theta^*, T_j) - \pi^d(\Theta^*, T_j)\right)/\kappa\right)}\right). \\ &= E\left(\frac{1}{1+\exp\left(\left(r(\mu_{c,\infty}^{in}(\Theta^*) + \mu_{c,\infty}^{out}(\Theta^*) - \mu_{d,\infty}^{in}(\Theta^*))(1-I^*/I) - \tau\overline{\lambda}\right)/\kappa\right)}\right) \\ &\geq 1/2. \end{aligned} \tag{44}$$

This means that, for the network with limited information to be disseminated, when the network cooperation ratio is Θ^*, the number of cooperators decreases. Similar to the argument in the Theorem 1, there exists a cooperation ratio $\Theta^{-,*}$ such that $P_{c\to d}(\Theta^{-,*}, T_j) = 1/2$, and the network reaches the ESS. We can see that $\Theta^{-,*} \leq \Theta^*$. Otherwise, according to the monotonic increasing property of $P_{c\to d}(\Theta, T_j)$, $P_{c\to d}(\Theta^{-,*}, T_j) > P_{c\to d}(\Theta^*, T_j) > 1/2$, which is a contradiction. □

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