Self-Interest-Driven Incentives for Ad Dissemination in Autonomous Mobile Social Networks

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***Abstract*—In this paper, we propose a Self-Interest-Driven (SID) incentive scheme to stimulate cooperation among selfish nodes for ad dissemination in autonomous mobile social networks. As a key innovation of SID, we introduce "virtual checks" to eliminate the needs of accurate knowledge about whom and how many credits ad provider should pay. A virtual check is included in each ad packet. When an intended receiver receives the packet for the first time from an intermediate node, the former authorizes the latter a digitally signed check, which serves as a proof of successful ad delivery. Multiple copies of a virtual check can be created and signed by different receivers. When a node that owns a signed check meets the ad provider, it requests the provider to cash the check. Both ad packets and signed checks can be traded among mobile nodes. We propose the effective mechanisms to define virtual rewards for ad packets and virtual checks, and formulate the nodal interaction as a two-player cooperative game, whose solution is obtained by the Nash Bargaining Theorem. Extensive simulations are carried out to compare SID with other existing incentive algorithms under real world mobility traces.**

I. Introduction

With its surging popularity among mobile users, social networking is experiencing unprecedented growth on smartphones and portable tablets. The transmission of social network contents between mobile users and social network sites (such as Facebook and Twitter) often rely on the underlying communication infrastructure, predominantly the Internet plus available wireless access networks (e.g., cellular and WiFi). However, Internet connection is not always available anywhere anytime or can incur an undesired extra cost.

In this research, we consider an *autonomous mobile social network* that does not depend on any infrastructure but, instead, exploits opportunistic connections among mobile users. More specifically, portable devices can communicate with each other and exchange social networking data via their short range radios (e.g., WiFi and Bluetooth) or licensed device-to-device (D2D) links. Such mobile device-to-device data transfer can increase network performance and reduce communication cost for both service providers and individual users [1], [2]. Due to the limited radio transmission range and unrestrained nodal mobility, the connection between mobile nodes is intermittent, forming a delay-tolerant network (DTN) setting [3]–[5]. An autonomous mobile social network is often created for a local community in which the participants have frequent interactions, e.g., people living in an urban neighborhood, students studying in a college, or tourists visiting an archaeological site. Its size varies from a large group (for instance, all students in a university) to a small cluster (such as members of a school band). It may serve a community over a long span of years, or be temporary to last for as short as a few hours only.

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A. Ad Dissemination in Autonomous Mobile Social Networks

Mobile social networking has a substantial impact on business. A survey [6] conducted by Google shows that 79% of smartphone consumers use their phones to help with shopping and 71% of them search after being exposed to advertisements online or offline. Therefore, dissemination of personalized ads is recognized as one of most promising mobile social network applications. The attractiveness of such an application lies in its simplicity, low-cost, convenience and efficiency. It is beneficial for small businesses looking to expand their customers, and attractive for individuals to publicize their personalized flyers. The advertisements to be disseminated fall into a range of categories, such as coupons, deals, newsletters, product catalogs, and extra show tickets. Each node in the network can be an ad provider or a receiver (or more commonly both). Ad providers (e.g., small local retailers, yard sale owners, and flea marketers) generate ads, which are disseminated to interested receivers directly or indirectly via other nodes. A mobile node may wish to receive ads in one or multiple ad categories. For instance, a saving mom may be interested in such ads as store coupons, baby clothing deals or grocery sale information. Ad dissemination via mobile social networks is highly effective, since the interaction among mobile users are closely correlated to their social groups and behaviors.

B. Selfishness and Incentives

However, mobile users in the real world can be either cooperative or selfish. A cooperative node carries and shares ads for others altruistically. On the other hand, if a node is selfish, it aims to maximize its own benefit only. Consequently, it is often reluctant to consume its energy, storage and bandwidth resources for nothing, and thus, refuses to carry any ads other than the ones interested by itself. Price-of-Anarchy, which measures how the efficiency of a system degrades due to selfish behavior of mobile nodes, is reported in [7] under four real social mobile network data sets. It demonstrates that data delivery ratio increases linearly with the decrease of selfish nodes. In other words, the more nodes contribute to relaying messages for others, the better performance the network achieves. Thus, to support such mobile ad dissemination in real world, an efficient incentive scheme is imperative to stimulate nodal cooperation and attract more participants.

In this work, we take selfishness into account, and assume a node is driven by its own interests. Ad dissemination is a "push" model, where a source intends to disseminate its ads, and thus, should pay for the delivery service. Other nodes participate in ad transmissions only if they are beneficiaries. This is in a contrast to other incentive models in the literature [8]–[10] where receivers intend to "pull" and consume data, and thus, are deemed as payers. In this paper, we assume

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all nodes are rational and honest. Neither do they consume their resources to help nor to maliciously attack others. We also assume strong authentication that provides auditability for the verification of identities of nodes and prevents forging identification to obtain free forwarding service or more rewards from others. The security related problems are out the scope of this paper and has been addressed in the literature [11]–[13].

C. Challenges and Contributions

Selfishness of mobile nodes has been studied in the context of mobile ad-hoc networks [8]–[10], [14]–[21]. For example, under the credit-based approaches, the source node learns the routing path and loads a number of credits in its data packet to pay each intermediate node that helps data delivery. A unique challenge to providing incentives in an autonomous mobile social network stems from its DTN-like opportunistic communication, where a routing path is nondeterministic. As a result, although the ad provider that intends to disseminate its ads should pay for the delivery service, it does not know how many nodes will involve in packet delivery and which nodes it should pay for. The problem is further complicated by packet duplication that is common in DTN, where multiple copies of a packet may be delivered to the same receiver but only the first copy should be paid. At the same time, a packet is often desired by multiple users who share the same interest, calling for equal incentives in such multicast deliveries. These characteristics together make the development of incentive mechanism for ad dissemination a unique, interesting, and challenging problem. As to be shown in Sec. II, none of the available schemes in the literature are directly applicable here.

Inspired by the charging-rewarding model [14], we propose a Self-Interest-Driven (SID) incentive scheme for ad dissemination in autonomous mobile social networks. A key innovation of SID is to introduce “virtual checks” to eliminate the needs of accurate knowledge about whom and how many credits ad provider should pay. The source loads a “virtual check” in an ad packet. When an intended receiver receives the packet for the first time from an intermediate node, the former makes a copy of the virtual check and digitally signs it, and authorizes the latter as the current owner of the signed check. The digital signature serves as a proof of the successful delivery of the ad packet. Multiple copies of a virtual check can be created and signed by different receivers. When a node that owns a signed virtual check meets the ad provider that issues the check, it requests the provider to cash the check (i.e., pay credits). Note that an ad provider only cashes signed checks issued by itself. Both ad packets and signed checks can be traded among mobile nodes. Since only the first deliverer is awarded the signed check, the key design issue is how to effectively track the potential value of a packet and how to have a signed check cashed by the ad provider as quick as possible under such an intermittent network setting. We propose effective schemes to define virtual rewards and checks, and formulate nodal interaction as a two-player cooperative game, with its solution obtained by the Nash Bargaining Theorem. Simulations are carried out to compare our proposed scheme with other existing incentive algorithms in terms of ad delivery rate, delay and overhead under real world mobility traces.

II. Related Work

Early studies on DTN predominantly focus on routing. Information dissemination is first addressed in PeopleNet [22], which mimics the way people disseminate information in real life via social contacts. It is based on epidemic dissemination, and thus, often inefficient under nonuniform mobility patterns. In [23], a social centrality metric is introduced based on social contacts and user interests to improve the efficiency of data dissemination. Optimal dynamic content distribution [24] addresses the problem of how to allocate bandwidth optimally to make the content at users as fresh as possible. In [25], a contact aware duplication algorithm is proposed for data sharing in inter-connectivity mobile network. Separately, FleaNet is proposed [26] for information sharing among people onboard vehicles. A probabilistic one-ownership forwarding algorithm is proposed in [27] to preserve privacy of electronic coupon [28] distribution. However, all of these dissemination schemes assume nodal cooperation in DTN.

Selfishness has been investigated in the context of mobile ad-hoc networks, largely under two categories: reputation-based (e.g., [15]) and credit-based (e.g., [16]–[18]) approaches. Their ultimate goal is to stimulate nodes to help by forwarding packets for others. However, these incentive approaches are not directly applicable in DTNs. The frequent partition and the lack of end-to-end contemporaneous paths in DTNs make it impractical for a node to manage reputation of its neighbors as required in the reputation-based approaches, or to estimate the number of intermediate nodes that would involve in packet forwarding as required in the credit-based schemes.

Several incentive mechanisms are developed recently for special DTN settings. For example, a barter-based scheme is proposed in [8] to stimulate cooperation in downlink *broadcast* transmission from a stationary source node to all mobile nodes in a DTN. A similar downlink scenario is considered in [9] but for *multicast* transmissions, where data packets in different categories are transmitted to different user groups. In [10], an incentive scheme is proposed for *data aggregation* in delay-tolerant sensor networks. In all of these scenarios, receivers are beneficiary and pay for data delivery services in one way or another. Clearly, they are different from the ad dissemination application studied in this work, where individual nodes can be data providers and push data packets to a set of receivers. Here the providers (or sources) must pay for data delivery, calling for new incentive mechanisms different from [8]–[10].

A handful of schemes are proposed to stimulate cooperation in general peer-to-peer DTN communications. In [20], if a relay node fails to show successful relay proofs, it is excluded from future communication. The hard and permanent penalty on selfishness leads to desired Nash equilibria but may result in improper punishment on normal nodes with random computation or communication failures. An incentive mechanism based on pairwise tit-for-tat (TFT) is presented in [21], where a node forwards as much traffic for a neighbor as the neighbor does for it. The TFT-based scheme requires each node to record how much traffic other nodes have relayed for it. In DTN, such information is often delayed, consequently degrading the performance. We will compare [21] with our work in Sec. IV.

III. Proposed Self-Interest-Driven Incentive Scheme for Ad Dissemination

A. System Overview

An autonomous mobile social network consists of a set of intermittently connected mobile nodes. In general, a mobile node varies its role as an *ad provider* or an *ad receiver* from time to time, or act as both simultaneously. An ad provider generates personalized ad packets in one or multiple ad categories, while an ad receiver wishes to receive ad packets in its favorite ad categories. *Virtual credits* are employed as currency to reward ad delivery service. The available credits at a node decrease when the node pays for delivery service for disseminating its own ads and increase when it provides delivery service for others. The details of how to pay and earn credits will be discussed in the next subsections.

An ad packet contains five fields: advertisement content, ad category, a virtual check, the maximum deliveries, and the time-to-live (TTL) that signifies the lifetime of the ad packet.

Definition 1. *The ad category β_p of Packet p indicates to which interest category Packet p belongs.*

The virtual check contains an unalterable unique ad ID (e.g., digitally signed by the provider) and a face value.

Definition 2. *The face value α_p of the virtual check in Packet p is the amount of virtual credits the ad provider is willing to pay to each intended receiver that receives the ad.*

The ad provider decides the face value of the virtual check. A higher face value means a stronger incentive, often resulting in a faster dissemination of the ad. The impact of face value on ad delivery will be quantitatively studied in Sec. IV. The virtual check is uncashable until it is signed by a receiver. When a copy of the ad is delivered to an intended receiver, a copy of the virtual check is signed and authorized to the deliverer as a reward.

Definition 3. *The* maximal deliveries *γ_p of Packet p is the maximum number of receivers to whom the provider intends to send the ad.*

It is bounded by the number of users in the network who are interested in the ad packet. $\alpha_p \times \gamma_p$ indicates the maximum number of credits the provider would like to pay for disseminating the advertisement, which must be limited by the total available credits at the provider. γ_p is often initialized by the provider according to the receiver population, which is the estimated number of receivers of the packet. The ad provider can learn this information by a counting algorithm [29]. γ_p is updated during dissemination as to be discussed later.

An example of the system is illustrated in Fig. 1, where each square represents a node, a dotted curve arrow indicates the movement of a node, and the solid arrow depicts communication. Mobile User A is a part-time car dealer and would like to promote his business by spreading used car deals to people in his community. Therefore, he creates an ad packet. When Nodes A and B meet, Node B acquires a copy of the ad packet via a trading process (to be discussed later). Node B is keen to have the ad because it routinely meets Node C (that is interested in used car deals) and thus has a high likelihood to gain rewards by delivering the ad packet. In the example depicted in Fig. 1, Node B subsequently transmits the ad packet to Node C, and in return, Node C makes a copy of the virtual check included in the ad packet, signs it, and authorizes the signed check to Node B as a reward for its delivery service. Note that, while User B holds the singed check, it has not yet obtained any credits. It has two choices. First, it may cash the check when it meets Node A. However, if it has an extremely low likelihood to meet Node A, this approach becomes infeasible. Although the check is still worth its face value, it is not much valuable to Node B. Thus, the second choice is to exchange the signed check with another node (e.g., Node E) for a signed check issued by a different provider to which Node B has a higher contact probability. Such an exchange should benefit both nodes (i.e., to increase their likelihood to cash checks). For example, Node E cashes the check when it meets Node A as illustrated in the figure. Obviously, the ad provider and receiver may also meet directly (see the meeting between Nodes A and D). In this case, the ad is delivered without issuing and cashing check.

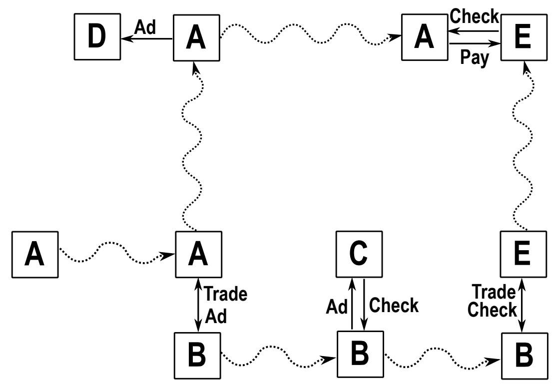

Fig. 1. An example of ad dissemination in a small community where each square represents a node, a dotted curve arrow indicates the movement of a node, and the solid arrow depicts communication. Node A is the ad provider while Nodes C and D are receivers.

Both ad packets and signed checks can be traded between two mobile nodes during ad dissemination. However, it is nontrivial to reach an agreement between them to decide which ad packet or signed check should be transmitted. Since nodes are all selfish, a node always tries to maximize its own benefit, which however may hurt the interest of the other node. For example, when a node acquires a copy of a packet from the other node, the former obviously increases its potential credits (because it adds a valuable packet into its inventory), but the latter suffers with a decreased potential benefit (since it just created a competitor, given a receiver only awards the first deliverer a signed check). Whenever a node wants an ad packet or signed check from the other node, it must trade one of its own for the desired packet. During the packet exchange, the nodes have conflicting interests, and the final agreement must do good to both of them. We thus observe that the nodes' bargaining process matches a two-person cooperative game, and model the action of each node from the game theory's perspective. The two nodes have different objectives and their interests can conflict with each other. To cope with conflict interests, the two person cooperative game allows players to reach a binding agreement. Given the selfish nature of the two persons, the binding agreement they reach must promote the interests of both nodes, based on the "values" of the packets and checks. Next, we introduce the effective mechanisms to define virtual rewards for ad packets and virtual checks, and formulate a two-player cooperative game to optimize such trading process, aiming to disseminate ad packets within their TTL to as many receivers as possible, and at the same time maintain a balanced budget.

B. Appraisal of Ad Packets and Virtual Checks

When two nodes encounter, they both want to properly trade their packets and/or checks in order to maximize their benefits. To decide which packets and checks should be traded, a node must appraise their values. The value of an ad packet mainly depends on two factors. First, an ad packet is more valuable to a node if the node has a higher likelihood to meet the receivers and consequently a higher chance to earn signed checks. Second, an ad packet with a higher maximum deliveries tends to have a higher value since a node that owns such a packet may potentially make deliveries to multiple receivers to obtain multiple signed checks. The second factor relates to the packet itself and remains the same for all nodes, while the first factor is node-dependent. Similarly, the value of a signed check to a given node is appraised based on its likelihood of being cashed.

Based on the above observations, we define two parameters, *Packet Virtual Reward* and *Check Virtual Reward*, to evaluate the value of an ad packet or signed check, respectively.

1) Packet Virtual Reward: To facilitate packet appraisal and trading, a node always creates virtual packets for each ad packet. Totally γ_p virtual packets for Packet p, which all link to the same advertisement content, face value, virtual check, ad category and TTL of Packet p, are created. But each virtual packet has its maximal deliveries set to one. The use of virtual packets effectively avoids the complexity in updating the maximal deliveries.

Let's consider Virtual Packet q that is one of the virtual packets created for Ad Packet p. Clearly, α_q=α_p, β_q=β_p, and γ_q=1. We estimate the potential value of Virtual Packet q by the *Packet Virtual Reward* which is denoted as R_n^q and signifies how many credits (on signed checks) Node n would gain if it trades in Virtual Packet q. Formally,

$$R_n^q = \alpha_q \times \xi_n^{\beta_q}, \tag{1}$$

where α_q is the face value of the virtual check included in the ad packet and $\xi_n^{\beta_p}$ is the *ad category contact likelihood (ADCL)*, i.e., the likeliness that Node n contacts the nodes that are interested in ads in Category β_q (i.e., potential receivers).

The ADCL of Node n in Ad Category i represents the likelihood that Node n delivers ads in Category i to interested receivers. Its value intrinsically depends on the aggregated direct and indirect contact likelihood with receivers. The former, i.e., the *direct* ad category contact likelihood, indicates the likeliness that Node i directly meets a node that is a receiver of Ad Category i. The latter captures the likelihood that Node i delivers ads to the receivers via other nodes indirectly. Similar to [9], we adopt the exponentially weighted moving average (EWMA), which is an effective scheme for online estimation, to maintain and update ADCL.

More specifically, each node maintains a timer. If there is no contact with other nodes within an interval of δ, the timer expires, generating a timeout event. Let η_n^i denote the direct contact likelihood of Node n with receivers in Ad Category i. It is initialized to zero, and updated at every contact with a receiver in Ad Category i or a timeout event, whichever comes first. η_n^i is updated as follows,

$$\eta_n^i = \begin{cases} (1-\epsilon_1)[\eta]_n^i + \epsilon_1, & \text{Contact,} \\ (1-\epsilon_1)[\eta]_n^i, & \text{Timeout,} \end{cases} \tag{2}$$

where $[\eta]_n^i$ is the direct contact likelihood of Node n with receivers in Ad Category i before it is updated, and $0 \le \epsilon_1 \le 1$ is a constant employed to keep partial memory of historic contact status. Similarly, let $\hat{\eta}_n^i$ denote the indirect contact likelihood of Node n with receivers in Ad Category i. When Node n meets Node k that is not a receiver in Category i, $\hat{\eta}_n^i$ is updated as follows:

$$\hat{\eta}_n^i = \begin{cases} (1-\epsilon_2)[\hat{\eta}]_n^i + \epsilon_2\eta_k^i, & \text{Contact,} \\ (1-\epsilon_2)[\hat{\eta}]_n^i, & \text{Timeout,} \end{cases} \tag{3}$$

where ϵ_2 is a constant between 0 and 1. One may wonder why the indirect contact likelihood should be considered here since a node only receives the signed check through direct delivery. The reason is that indirect contact likelihood can help nodes to trade valuable packets. For example, we assume Node A owns Packet p in Category i, but has a low direct contact likelihood to any receivers in Category i. At the same time, Node B has a high direct contact likelihood to receivers in Category i. When Nodes A and B meet, Packet p can be a very competitive packet for Node A to trade with Node B. Thus, the indirect contact likelihood also contributes to ad delivery and rewarding process. As shown in [30], two-hop relaying achieves most performance gains. Therefore, we assume indirect contacts involve two-hop relaying only in the following discussions. Since the direct transmission and two-hop relaying are independent, we have the ADCL of Node n in Ad Category i:

$$\xi_n^i = 1 - (1-\eta_n^i)(1-\hat{\eta}_n^i). \tag{4}$$

Let Φ_n denote the set of ad packets owned by Node n. Their total value is $R_n = \sum_{p\in\Phi_n} R_n^p$.

2) Check Virtual Reward: Similar to the packet virtual reward discussed above, we introduce the *Check Virtual Reward*, denoted as C_n^c, to indicate the value of Signed-Check c to Node n:

$$C_n^c = \alpha_c \times \rho_n^c, \tag{5}$$

where α_c is the face value of the check and ρ_n^c is the *check reward contact likelihood (CRCL)*, i.e., the likeliness that Node n meets the issuer of Check c. ρ_n^c represents the likelihood that Node n contacts the payer of Check c directly or indirectly. The method to obtain CRCL is similar to Eqs. (2)-(4), but based on individual nodes instead of categories. Thus, the details are omitted here. The total value of all checks owned by Node n is $C_n = \sum_{c\in\Psi_n} C_n^c$, where Ψ_n denotes the set of signed checks at Node n.

3) Self-Interest Gain: Assume Node n meets and trades packets and checks with another node. Let Φ_n and $\hat{\Phi}_n$ be the set of ad packets owned by Node n before and after the trade. Similarly, Ψ_n and $\hat{\Psi}_n$ denote the set of checks before and after the trade, respectively.

We define the self-interest gain that Node n achieves by trading ad packets as follows:

$$s_n^a = \sum_{p \in \hat{\Phi}_n} R_n^p - \sum_{p \in \Phi_n} R_n^p, \tag{6}$$

and the self-interest gain by trading checks as:

$$\tilde{s}_n^c = \sum_{c \in \hat{\Psi}_n} C_n^c - \sum_{c \in \Psi_n} C_n^c. \tag{7}$$

Clearly, the positive gains are expected by Node n. Note that, the queue of a node is likely full at the steady state. Receiving a packet means to replace an existing packet with the lowest expected reward. The loss of such a packet is taken into account in the calculation of self-interest gain, i.e., the dropped packet is excluded from Φ_n in Eq. (6).

C. Cooperative Game Model for Trading Packets and Checks

With limited initial credits, how to maintain a balanced wallet and at the same time distribute as many ads as possible is crucial for every node. None of the nodes want to waste their own resources to help others due to their social selfishness. Like in a real-life market, in order to maximize their own benefits, the nodes often ask for different packets and checks to trade, and negotiate transactions through bargaining. To this end, we formulate the interaction between two nodes as a two-player cooperative game originally proposed by John Forbes Nash in [31]. The two players in the game are rational and selfish. They negotiate to cooperate in making decisions on trading, such that each of them can maximize its benefit. We assume that the ad packets and checks are traded separated, and show that the trading process can be solved using the Nash bargaining solution.

To facilitate our exposition, we first define the two player bargaining problem as follows, and then give an overview on how to apply Nash bargaining solution to trade the ad packets and checks, followed by an analysis of the game.

1) Two Player Bargaining and Nash Bargaining Solution: We formulate the nodal interaction as a two-player cooperative game, where the players reach a agreement via bargaining.

Definition 4. *The* two player bargaining problem *is defined as the pair (S, d), where S defines the space as the set of all possible utilities that the two player can achieve, i.e.,* (s_n, s_k)*, and* $d \in S$ *is the* disagreement point, *usually defined as the utility gain without cooperation, i.e.,* (d_n, d_k)*, such that there exists some* $s \in S$ *and* $s > d$*, i.e.,* $s_n > d_n$ *and* $s_k > d_k$ *[32].*

Each player can choose its strategy, i.e., a set of packets or checks that it wants to get. When an agreement is reached by two players, the self-interest gains (s_n, s_k) are their payoffs. Note that the gain of one player depends on the strategies chosen by both of them. In a contrast to the non-cooperative game, the two-player cooperative game allows players to reach a binding agreement, despite their possibly conflicting interests. The selfishness of the players ensures that, the binding agreement, once reached, must benefit both players. There exist many kinds of cooperative game solutions. Among them, the Nash bargaining solution provides a unique and fair Pareto optimal point. It is briefly described as follows.

The Nash bargaining solution [31] for a two-person cooperative game is given by

$$(\hat{s}_n, \hat{s}_k) = arg \max_{(s_n, s_k) \in S} (s_n - d_n) \times (s_k - d_k), \tag{8}$$

where s_n and s_k are the utility gains of Node n and Node k, respectively, $(\hat{s}_n, \hat{s}_k)$ is the optimal solution, which is also the utility gain of Node n and Node k in the Nash solution, and d_n and d_k is the disagreement points, $(s_n - d_n) \times (s_k - d_k)$ is called the Nash product.

2) Proposed Incentive Protocol: We formulate the trading process as a two-player cooperative game as discussed above and apply the game model to ad packets and checks independently, i.e., a packet can not be traded with a check. Standard optimization method can be employed to obtain the Nash bargaining solution given in Eq. (8). More specifically, we propose an incentive protocol with five steps outlined below.

- Step (1) Each node periodically performs neighbor discovery. When Node n meets Node k, it first updates its ADCL and CRCL. Then it learns the available ad packets and checks at Node k, i.e., Φ_k and Ψ_k, and creates a packet candidate list $\hat{\Gamma}_n = \Phi_k - (\Phi_n \cap \Phi_k)$ and a check candidate list $\check{\Gamma}_n = \Psi_k - (\Psi_n \cap \Psi_k)$. $\hat{\Gamma}_n$ and $\check{\Gamma}_n$ are sorted in a decreasing order of the packet virtual rewards and check virtual rewards, respectively. They are essentially the packets and checks available at Node k but not at Node n. Here, we have assumed two nodes meet only, which is largely true in a DTN-like mobile social network where nodal density is low. If more than two nodes meet, a node randomly chooses another node that is not involved in any communication to trade.
- Step (2) Node n checks if it is a receiver for any packets in $\hat{\Gamma}_n$. If it is, Node n requests those packets from Node k. For each received packet, e.g., Packet p, Node n makes a copy of the virtual check, digitally signs it and authorizes it to Node k. Note that Node k still keeps a copy of Packet p. Upon receiving the signed check, Node k decreases the maximum deliveries of Packet p by one, i.e., $\gamma_p = \gamma_p - 1$.
- Step (3) Node n checks if it is a payer for any checks in $\check{\Gamma}_n$. If it is, it pays Node k a number of credits equal to the total face values of the checks and Node k removes those checks from Ψ_k. At the same time, Node k examines if it is a receiver or payer similarly.
- Step (4) Nodes n and k bargain which packets and checks should be traded. This process is formulated as a two-player cooperative game as discussed above.
- Step (5) Finally, they transmit to each other the set of ad packets and checks determined by the Nash bargaining solution.

The above proposed scheme assumes the virtual packets are traded separately. In real implementation, the virtual packets should be consolidated to ad packets. For example, assume Node n currently owns Packet p with a maximum deliveries of γ_p, and the two-player game suggests Node n to transmit x virtual packets of Packet p to Node k. What Node n will really do is to create two copies of Packet p. It keeps one copy with the maximum deliveries updated to $\gamma_p - x$, and transmits the other copy with a maximum deliveries of x to Node k.

3) Analysis of the Game Solution: The proposed incentive scheme owns several desired properties. First we show the proposed scheme can achieve network-wide Pareto optimality.

Lemma 1. *The proposed incentive protocol achieves network-wide Pareto optimality at the convergence in a static network.*

Proof: We prove it by contradiction. Given a static network, if the result is not Pareto optimal after convergence, there must exist some users that can improve their performance without hurting the others'. Note that the nodes intend to find the Nash bargaining solution for an individual bargain process, which by itself is Pareto optimal as shown in [31]. Thus, those users can bargain via the proposed scheme to improve their performance. This means the convergence is not achieved yet, which is contradictory. Therefore the lemma is proven. ■

Besides Pareto optimality, the Nash bargaining solution also satisfies three other axioms: symmetry, independence and invariance. The symmetry axiom indicates that if the feasible solution for both users are symmetric, then they have the same solution. The independence axiom shows that eliminating the feasible solutions that would not have been chosen should not affect the Nash bargaining solution. The invariance means the bargaining solution is scale-invariant.

The convergence of the trading process is upper bounded, and the bound can be calculated by a genie-aided centralized algorithm. Since the solution is pair-wise-based, no bargain deal will be reached if the mutual benefits cannot be obtained. As a result, the performances will monotonously increase. Due to the monotony and bound, the proposed solution converges for a static network. In practice, the network is dynamic. But as long as the bargaining frequency is sufficient, the network performance is always improved by the proposed scheme.

IV. Performance Evaluation

In this section, we present the simulation results to demonstrate the efficiency of our proposed incentive scheme.

A. Competing Algorithms

PROPHET [33] is chosen as the baseline for comparison. It is a probabilistic DTN routing algorithm, without consideration of selfishness. Under PROPHET, a node always forwards a packet to a node with a higher delivery likelihood to the destination. Since PROPHET does not consider selfishness of mobile nodes, we implement its two variants. The first (denoted as "ProphetSlefish") is under the assumption that all nodes are selfish. Thus, a node only receives its interested ad packets directly from ad providers. In the other variant named "ProphetCooperative", we assume that nodes are cooperative and altruistic. A node always choose the most valuable packets to carry for others after satisfying its own interests.

The pair-wise tit-for-tat (TFT) scheme is proposed in [21] where a node forwards as much traffic for a neighbor as the neighbor forwards for it. In general, TFT is developed for peer-to-peer communication in DTN. Therefore, several techniques (such as link state dissemination, route computation and ACK feedback updates) adopted in TFT appear overkilling for ad dissemination, often exhibiting undesired overhead and long delay under this application. As discussed in Sec. II, since other DTN data dissemination algorithms [8]–[10] are designed under different application scenarios where receivers are payers, they are incomparable with our proposed scheme.

TABLE I
Overall performance comparison based on Haggle trace.

	Delivery Rate	Average Delay	Overhead
ProhetSelfish	0.31	21598s (5.9h)	1
ProphetCooperative	0.78	4533s (1.25h)	19
TFT	0.71	17587s (4.88h)	6
SID	0.83	8078s (2.24h)	3

B. Simulation Setup

Two representative social network data sets obtained from the Cambridge Haggle project [34] and the UMass DieselNet project [35] are employed in our simulations. The former involves 98 iMotes and Bluetooth devices and runs for a period of about 3 days. The latter is based on a DTN testbed with 30-40 transit buses, serving an area of approximately 150 square miles. Our simulation is based on the trace data obtained in 2006 with 37 buses for a period of about two weeks.

Thirty ad categories are defined in our simulations. Each node has a default queue size for 200 packets and initial credits of 100. When a node acts as an ad provider, it generates one ad packet every 15 minutes in a random ad category. At the same time, a node is also interested in receiving ads in 5 randomly chosen ad categories. Given the small size of a check, we assume that nodes can hold as many signed checks as possible. The TTL of a packet is set to infinity by default. For simplicity, the face value of a virtual check is set to one. The values of ϵ_1 and ϵ_2 in Eq. (2) and Eq. (3) are 0.1 and 0.2, respectively.

C. Performance Comparison

We are interested in the following metrics for performance evaluation: the packet delivery rate, the average delivery delay, the transmission overhead, and the credit distribution among nodes. The delivery rate is defined as the ratio of the total number of delivered packets to the total number of ad packets that should be disseminated to corresponding receivers. The average delivery delay measures how long a node waits to get an interested ad packet. The transmission overhead is a cost factor, defined as the ratio of the total number of transmissions to the total number of delivered packets. Lower overhead means less traffic in the network and lower resource consumption. We assume the control packet is much smaller than the data packet, and therefore, its overhead is negligible. We further analyze the average number of packets exchanged between two nodes when they encounter. The virtual credit distribution depicts the degree of cooperation among nodes. The more credits a node owns, the more cooperative it is.

Tables I and II compare the overall performance of different schemes based on the Haggle trace and the DieselNet trace, respectively. As can be seen from both tables, the data delivery rate of SID is very close to "ProphetCooperative", the cooperative scheme. The high packet delivery rate of SID is attributed

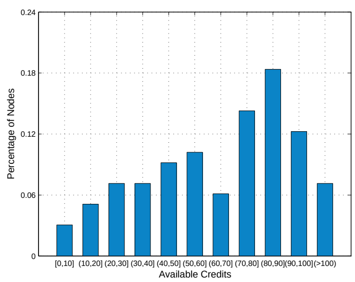

Fig. 2. Distribution of available credits.

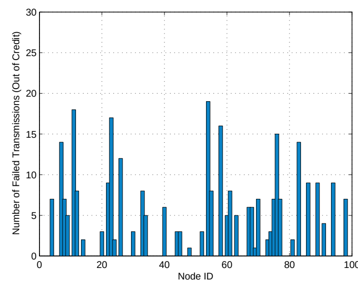

Fig. 3. Failed transmissions due to lack of credit.

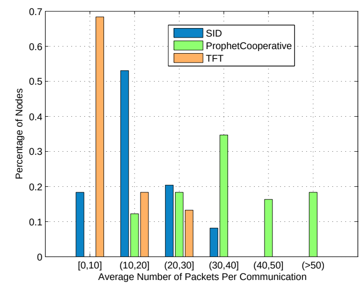

Fig. 4. Average number of packets per transmission.

TABLE II
OVERALL PERFORMANCE COMPARISON BASED ON DIESELNET TRACE.

	Delivery Rate	Average Delay	Overhead
ProhetSelfish	0.19	49672s (13.79h)	1
ProphetCooperative	0.81	10594s (2.94h)	16
TFT	0.70	25729s (7.16h)	5
SID	0.79	12387s (3.44h)	4

to the fact that a node is well stimulated to forward others' packets, which it likely makes a delivery and thus gains credits, leading to highly efficient data transmission in the autonomous mobile social network. It is interesting to observe SID even achieves a higher delivery rate than ProphetCooperative under the Haggle trace as shown in Table I. This is anti-intuitive, because the nodes are altruistic under ProphetCooperative to carry each other's packets voluntarily, and thus, the delivery likelihood should be the highest. However, altruism can be a double edged sword. While altruism makes nodes willing to accept others' packets, it may cause many packets be dropped before success delivery. This is because full cooperation always makes packets flow to a certain group of nodes who are active in the network. Packets are sometimes aggregated quickly, and thus, dropped due to buffer overflow. At the same time, we notice that although the TFT scheme considers nodal selfishness, its delivery rate is lower than SID, because maintaining a mutual forwarding balance wastes useful contact opportunities. In SID, the estimated value of packets effectively fosters cooperation among nodes and makes efficient use of communication resource (that is determined by the capacity of nodes and their meeting opportunities), thus leading to a higher delivery rate. Finally, nodes under ProphetSelfish do not cooperate at all, resulting in the lowest delivery rate.

The ProphetCooperative and SID exhibit much shorter average delay than other schemes, because both of them leverage the packet value to estimate the probability to deliver the packet and choose the best routes to forward it, thus delivering the packet in a shorter time. It is no surprise to observe the longest delay under ProphetSelfish because an ad packet is only delivered from its provider to the receiver directly. Although the source in TFT scheme specifies complete route for each generated packet, packets may not always flow along the best routes due to the TFT constraint and results in a longer delay. Moreover, we can see that the ProphetCooperative has a much higher overhead than SID, because its altruism leads to more packets to be duplicated and distributed in the network. In a contrast, SID achieves low overhead, since a node receives a packet only if it can gain benefits from the packet.

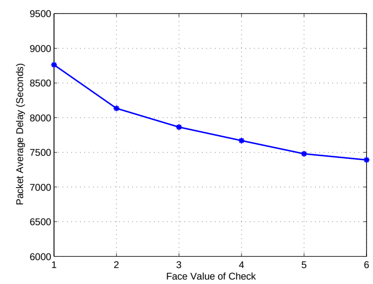

Fig. 5. Impact of check's face value on packet delivery delay.

Fig. 2 illustrates the distribution of available credits under SID. Credits are consumed for ad dissemination. The more credits a node owns, the more ad packets it can disseminate. Most nodes have their available credits lower than 100, because they have on-going ad dissemination, and thus, have held some credits to be paid for corresponding receivers. Such credits are not included as "available credits" in Fig. 2. About 40% of nodes can keep their available credits around $70-100$, comparing to 100 initially. It indicates that they maintain a good balance of credit producing and consuming, and can continuously disseminate their own ad packets. An analysis of failed transmissions (due to short of credit) is depicted in Fig. 3. About half of the nodes do not have any failed transmissions and the average number of failed transmissions is less than 5, showing that the two-player cooperative game promotes win-win trade for both nodes to obtain gains and prevents unilateral benefit causing starvation. The nodes that suffer failed transmissions are due to the lack of cooperation opportunities which consequently leads to credit shortage.

Fig. 4 shows the average number of packets exchanged per communication between two encountering nodes. The more packets are exchanged, the more resources are consumed. As can be seen, about 68% of nodes in TFT exchange less than 10 packets per communication. This is mainly due to the TFT constraints that enforce bilateral balances. In ProphetCooperative, about 70% of nodes exchange more than 30 packets per communication. It is noticed that some very active nodes intend to transmit and receive a large number of packets, consequently leading to frequent overflow and packet dropping. In SID, mobile nodes strike a balance between their individual interests and contribution to the network. Most nodes exchange 10-20 packets per communication.

To evaluate how the face values of checks impacts the performance of packet delivery delay, we randomly choose a source node (e.g., Node 66) and gradually increase its check's face value from 1 to 6 credits, while all other nodes still keep a face value of 1 credit for their checks. The result is shown in Fig. 5. As can be seen, the average packet delivery delay decreases with the increase of check's face value. This is because a higher face value indicates more rewards that can be obtained if a node successfully delivers the packet, or in other words, stronger incentives to stimulate nodal collaboration.

Figs. 6-8 illustrate the performance trend by varying such network parameters as queue size, traffic load and TTL. Both traces show similar trend. Figs. 6-8 are based on the Haggle trace only. With the increase of the queue size, the delivery rate of all schemes increases (see Fig. 6). Particularly, ProphetCooperative gains significantly, because a longer queue allows a node to hold more data packets for a longer time, thus increasing the probability of packet delivery. As a side effect, a longer queue results in a surge of overhead, because more duplications can be hold and transmitted by the mobile nodes. In addition, the delay also increases. One may expect that a larger queue should decrease the delay in ProphetCooperative since it can carry more packets, and thus, increases the chance for the packets to meet their receivers. However, a larger queue also means packets even with a low delivery probability can find a place to stay. When such packets get delivered, they have already experienced long delay, thus increasing the average network delay. On the other hand, the increase of the queue size affects the performance of TFT and SID only marginally, since TFT is constrained by the amount of traffic forwarded for others and SID exchanges the packets based on its self-interest and aims to maximize its rewards. Neither of them aggressively utilize the increased buffer size.

To evaluate the performance of the schemes under different amounts of traffic load, we vary the packet generation rate from one packet per 30 minutes to one per 5 minutes per node. As depicted in Fig. 7, with the increase of traffic load, a lower delivery rate is observed under all schemes, but in different degrees. The delivery rate of SID only degrades slightly, while the TFT and ProphetCooperative schemes experience more than 20% reduction of their delivery rates when the packet generation rate reaches one per 5 minutes. The increase of traffic load also results in a longer delay, because more packets are pushed into the network and they must wait in queues for a longer time before being delivered. The overhead increases too, since more packets are transmitted and duplicated.

The TTL of a packet indicates how long the packet can live in the network. It is set by the ad provider at the time of packet generation. In the previous simulations, we assume that the packet TTL is infinite. Now, we change the TTL from 0 to 7 hours to see its impact on the delivery ratio, delay time and transmission cost. As shown in Fig. 8(a), all schemes can deliver more packets to the destinations under a longer TTL, until the communication capacity of the network becomes the bottleneck and dominates the network performance. Fig. 8(b) shows the average delay time. We notice that the average delay of ProphetCooperative and SID tends to become stable after TTL increases to 4 hours, while the delay of ProphetSelfish and TFT continues to increase with longer TTL. It means that in ProphetCooperative and SID schemes most packets can be delivered within 4 hours, while ProphetSelfish and TFT need to keep packets stay longer in the nodal buffer. Fig. 8(c) shows the overhead with the increase of TTL. We observe that when TTL is increased from 1 to 3 hours, the overhead of all schemes increases, especially for ProphetCooperative. This is because extending TTL allows packets stay longer in the network, which thus has a better chance to be exchanged and duplicated, yielding more overhead.

V. CONCLUSION

We have proposed a Self-Interest-Driven incentive scheme to stimulate cooperation between selfish nodes for ad dissemination in autonomous mobile social networks. Our studies have shown that a unique challenge to provide incentives in an autonomous mobile social network stems from its opportunistic communication where a routing path is nondeterministic. The problem is further complicated by the existence of duplications, multiple receivers, and multiple ad categories. To this end, we have introduced "virtual checks" to eliminate the needs of accurate knowledge about whom and how many credits ad provider should pay. Both ad packets and signed virtual checks can be traded between mobile nodes. We have proposed effective mechanisms to define virtual rewards for ad packets and virtual checks, and formulated nodal interaction as a two-player cooperative game. Extensive simulations have been carried out for evaluation and performance comparison under the real world mobility traces.

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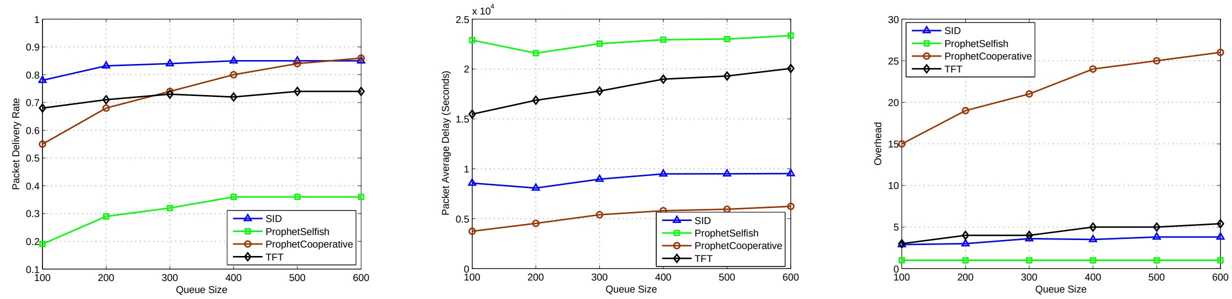
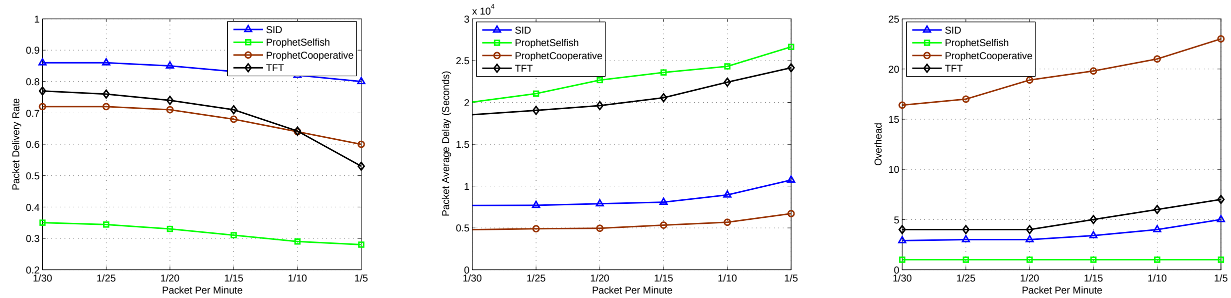


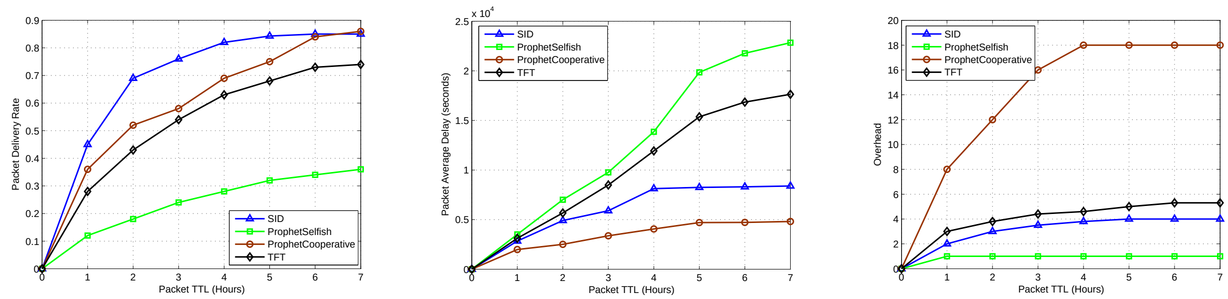
(a) Reception Rate. (b) Average Packet Delay. (c) Transmission Overhead.

Fig. 6. Performance trend with increasing queue size (under the Haggle trace).



(a) Reception Rate. (b) Average Packet Delay. (c) Transmission Overhead.

Fig. 7. Impact of packet generation rate (under the Haggle trace).



(a) Reception Rate. (b) Average Packet Delay. (c) Transmission Overhead.

Fig. 8. Packet reception rate, average delay and overhead under varying packet TTL (under the Haggle trace).

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