A Bargaining-Based Approach for Incentive-Compatible Message Forwarding in Opportunistic Networks

Fan Wu[†] Tingting Chen[§] Sheng Zhong[⋆] Chunming Qiao[⋆] Guihai Chen[†]

[†] Department of Computer Science and Engineering, Shanghai Key Laboratory of Scalable Computing and Systems, Shanghai Jiao Tong University, China

[§] Department of Computer Science, Oklahoma State University, USA

[⋆]Department of Computer Science and Engineering, SUNY at Buffalo, USA

fwu@cs.sjtu.edu.cn; tingting@cs.okstate.edu; {szhong, qiao}@buffalo.edu; gchen@cs.sjtu.edu.cn

Abstract—**Opportunistic networking is an important technique to enable users to communicate in an environment where contemporaneous end-to-end paths are unavailable or unstable. To support end-to-end messaging in opportunistic networks, a number of probabilistic routing protocols have been proposed. However, when nodes are selfish, they may not have incentives to participate in probabilistic routing, and the system performance will degrade significantly. In this paper, we present a novel incentive scheme for probabilistic routing that stimulates selfish nodes to participate. We not only rigorously prove the properties of our scheme, but also extensively evaluate our scheme using GloMoSim. Evaluation results show that there is an up to 75.8% gain in delivery ratio compared with a probabilistic routing protocol providing no incentive.**

I. Introduction

With the broad deployment of mobile wireless devices, *opportunistic networking* is becoming increasingly important in Mobile Ad-Hoc Networks (MANETs) and Delay-Tolerant Networks (DTNs), as well as mobile social networking applications. Opportunistic networking techniques enable users to communicate in an environment where contemporaneous end-to-end paths are unavailable or unstable. In such an environment, due to transitivity of links, messages are usually passed from one user to another in a store and forward fashion. Forwarding opportunities arise whenever mobile devices/users come into the communication range of each other. In contrast to traditional networking techniques, in which messages are delivered along preexisting end-to-end paths, opportunistic networking allows a message to be transferred from its source to its destination even when such a path from the source to the destination never exists.

In recent years, many routing protocols have been proposed to support end-to-end messaging in opportunistic networks (see [7] for a survey). A large portion of these existing protocols (*e.g.*, [2], [10]) are *probabilistic routing protocols*. In probabilistic routing protocols, when a node carrying a message meets another node, it estimates the probability of the latter node being able to bring the message to the destination. This probability is used to decide whether the message should be forwarded to the latter node or not. Existing research has shown that probabilistic routing is a very practical and effective technique in opportunistic networking.

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The adoption of such probabilistic routing protocols, however, might lead to reduced network performance when nodes have selfish behavior. In particular, opportunistic networks, like many distributed autonomous systems, suffer from common incentive problems such as the free-rider problem [1] when nodes are selfish. If selfish nodes are not appropriately rewarded, they do not have incentives to behave cooperatively. Hence, the performance of the network could degrade significantly, because only a small fraction of user nodes contribute their resources. Therefore, it is crucial to have a good incentive scheme that stimulates selfish nodes to cooperate in probabilistic routing.

Although much progress has been made in designing incentive schemes for wireless networks [4], most of existing incentive schemes are based on contemporaneous end-to-end connections, and thus do not apply to probabilistic routing. It is still an open problem to design incentive schemes for probabilistic routing. The objective of this paper is to study this open problem. Specifically, we would like to answer this question: if we are given a probabilistic routing protocol, how can we make it incentive compatible? That is, how can we enhance a probabilistic routing protocol such that selfish nodes will have incentives to cooperate when using this protocol?

To answer this question, we propose an approach based on *bargaining*. Bargaining theory [11], [12] captures both the competitive property and the positional property of a negotiation process between two or more parties. The intersecting yet conflicting interests of the different parties lead to a game between the involved parties, through which an agreement is reached.

In this paper, we model the message exchange process between a pair of nodes in probabilistic routing as a bargaining game. Hence, when a message is transferred from its source to its destination, it goes through a series of bargaining game. In each of these games, the message is traded from its current carrier to a node with even higher valuation. When this series of bargaining games is completed, the message reaches its destination. Based on analysis of the bargaining game,

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we design an incentive scheme that stimulates cooperative behavior in probabilistic routing. Below is a summary of our contributions in this paper:

- We model the process of probabilistic routing as a series of bargaining game.
- We present a novel and practical scheme to make a broad class of probabilistic routing protocols incentive compatible. We rigorously prove that, if our incentive scheme is used, there exists a unique subgame perfect equilibrium, in which nodes behave cooperatively. Here, intuitively, subgame perfect equilibrium means that a player can not get more benefit by unilaterally deviating from the equilibrium strategy in any subgame starting at her move. So, being cooperative is always to the best interests of the selfish nodes.
- We extensively evaluate our scheme using GloMoSim. Our evaluation results verify that, with our scheme, participation is to the best interest of each node, and there is an up to 75.8% gain in delivery ratio if compared with a probabilistic routing protocol having no incentive provided.

The rest of this paper is organized as follows. In Section II, we present technical preliminaries. In Section III, we present our message trading scheme to achieve incentive compatibility for probabilistic routing. In Section IV, we report evaluation results. In Section V, we review related works. In Section VI, we draw conclusions.

II. Technical Preliminaries

Before presenting our system architecture and developing our scheme, we first review the probabilistic routing protocols we consider. We also review relevant game theoretic solution concepts.

A. Basic Probabilistic Routing Protocol

We assume we are given a *basic probabilistic routing protocol*, which is an abstraction of a broad class of probabilistic routing protocols. Probabilistic routing protocols are based on the observation that, in practice, nodes are not likely to move around randomly, but rather move in a predictable fashion based on mobility patterns. If a pair of nodes has met several times before, it is likely that they will meet again in the future. Such mobility patterns can be exploited to improve performance of routing protocol in opportunistic networks.

To exploit the mobility patterns, a probabilistic metric called delivery probability was introduced. Let $P_{a,b} \in [0,1]$ be the delivery probability from node a to a destination node b. This metric indicates how likely that a node will be able to deliver a message to the destination. Each node stores a matrix of delivery probabilities. When two nodes meet, they exchange their delivery probability matrices. This matrix is used to update the internal delivery probability matrix. Then the delivery probability matrix is used to decide which message to forward from one node to another.

Formally, a basic probabilistic routing protocol works as follows.

Forwarding Algorithm: When a node a meets another node b, they perform a message exchange through a number of steps. First, node a gives node b a list of the messages node a carries as well as their destinations. Each message is also annotated by a with a's delivery probability. Node a receives the same list from node b and calculates its delivery probabilities of node b's messages. Node a then requests from node b the messages of which it has higher delivery probability than node b by at least θ.

Delivery Probability Calculation: The calculation of the delivery probability has two parts. The first part is to calculate each node's probability of meeting each of the other nodes. Let $\rho_{a,b}$ be the estimated probability that node a and node b meet. Here $\rho_{a,b}$ is computed based on the recorded movement events of the nodes during the last τ time slots, where a time slot is a fixed length of time (*e.g.*, 1 hour or 1 day, depending on the movement speed of a typical node). The basic probabilistic routing protocol specifies a function $f_1()$, which computes

$$\rho_{a,b} = f_1\left(\left\{e_{a,b}^{t-\hat{t}} | \hat{t} \in \{1, 2, \ldots, \tau\}\right\}\right),$$

where t is the current time slot, $e_{a,b}^{t-\hat{t}}$ indicates whether node a and node b met in time slot $t - \hat{t}$.

Next, the transitive property of previously computed meeting probabilities is exploited to calculate the delivery probability $P_{a,b}$. The basic probabilistic routing protocol also specifies a function $f_2()$, which computes

$$P_{a,b} = f_2\left(\{(a, b, \rho_{a,b}) | a, b \in V\}\right),$$

where V is the set of nodes in the system.

Note that, by using different functions for $f_1()$ and $f_2()$, we can get different instances of basic probabilistic routing protocol. For example, PROPHET [10] and MV [2] are both instances of the basic probabilistic routing protocol. Protocols in [5], [6] are also instances of this class after scaling the estimation to the range $[0, 1]$.

As we have mentioned, the existing probabilistic routing protocols lack incentive mechanisms, and accordingly selfish intermediate nodes may not be willing to forward messages for others for free.

B. Game Theoretic Model and Solution Concepts

To study the incentive compatibility of probabilistic routing, we model the message forwarding process as a *bargaining game* [12].

Specifically, we isolate a pair of nodes, who come into the communication range of each other, and model the interaction between them for the possible transfer of a message as a bargaining game. One of these two nodes is the current carrier of the message. It determines whether to forward the message to the other node. We view this process as *bargaining*, where the current carrier of the message is the seller of the message, and the other node is the buyer. Hence, there are two players in the game, the seller S and the buyer B. The set of players is $N = \{S, B\}$. These two players need to agree on a price at which S sells the message to B.

The bargaining game is played in rounds. In each round, the seller S makes a proposal, then the buyer B decides to accept it or not. Acceptance ends the game while rejection leads to the next round. A strategy s_i of player $i \in N$ is a function that assigns an action to player i when it is its turn to move. As a notational convention, $-i$ represents the player other than player i in the bargaining game. Similarly, s_{-i} represents the strategies of the player other than player i. Note that $s = (s_i, s_{-i})$ is a strategy profile.

If an agreement on purchase price x is reached in round r, then the two players' utilities are:

$$\begin{aligned} u_S &= x - V_S(m) - T(m) - c_S(r), && (1)\\ u_B &= V_B(m) - P(m) - x - c_B(r), && (2) \end{aligned}$$

where $V_i(m)$ is the valuation of message m to player i, $T(m)$ and $P(m)$ are the costs associated with the transmission and reception of message m, $c_S(r)$ and $c_B(r)$ are the bargaining costs of seller S and buyer B in the procedure of the game.

We note that $V_i(m)$ is the integrated message valuation of node i and its downstream nodes. In a bargaining game, if $-i$ is i's downstream node, then $V_{-i}(m) - V_i(m) - T(m) - P(m)$ is this game's profit margin.[1] $V_i(m)$ is determined as follows: assume that whoever delivers message m to the destination node can get a payment ω from the source node. Considering the previously defined delivery probability $P_{i,d}$, the valuation of a message m at node i is as follows.

$$V_i(m) = \omega \cdot P_{i,d}.$$

Clearly, a node with a higher delivery probability of a message also has a higher valuation of the message. Hence, a node has incentives to purchase the message from nodes who have lower delivery probabilities. (Consequently, the message is forwarded to the node with higher and higher delivery probability, and finally reaches the destination.) For simplicity, we assume that the source and the destination nodes in a session are trustworthy, and do not consider their utilities in this work. However, we will consider the case in which both the source and the destination nodes act as game players in our future work.

Assume that each of the two player nodes S and B incurs a cost (*e.g.*, power consumption) $\sigma > 0$ for every round of the game. Then we have $c_S(r) = c_B(r) = r \cdot \sigma$.

Let R be the maximum number of rounds for bargaining. If the players do not reach any agreement after R rounds of bargaining, then their utilities are

$$\begin{aligned} u_S &= -c_S(R), && (3)\\ u_B &= -c_B(R). && (4) \end{aligned}$$

In Section **??**, we assume that the value of R is known by all nodes.[2] We also assume that the players always keep bargaining for the possible message exchange, until an agreement is reached or the bargaining reaches the last round.

Bargaining game is a special case of extensive game with perfect information [12]. In an extensive game with perfect information Γ, a history h is a sequence of actions starting from the beginning of the game. A subgame is the remaining part of the game following a specific history. Denote by $\Gamma|_h$ the subgame that follows the history h. Let $s_i|_h$ denote the strategy that s_i induces in the subgame $\Gamma|_h$, and $u_i|_h$ denote the utility of player i in subgame $\Gamma|_h$. We now review commonly used solution concepts for extensive game with perfect information.

In extensive games, an important solution concept is *subgame perfect equilibrium* [12]:

Definition 1 (Subgame Perfect Equilibrium): A subgame perfect equilibrium of an extensive game with perfect information Γ is a strategy profile $s^\star$ such that for every player $i \in N$ and every nonterminal history h, after which it is player i's turn to take an action, we have

$$u_i|_h(s_i^\star|_h, s_{-i}^\star|_h) \geq u_i|_h(s_i, s_{-i}^\star|_h),$$

for every strategy s_i of player i in the subgame $\Gamma|_h$.

The game studied in this paper has a finite horizon, which means that the number of rounds is finite and the number of actions at any round is finite.

We can restrict our attention, for each player i and each subgame, to alternative strategies that differ from $s_i^\star$ in the actions they prescribe after just one history. That is to say, a strategy profile is a subgame perfect equilibrium if and only if in each subgame the player who makes the first move cannot obtain a better utility by changing only his initial action.

III. Message Trading Scheme

In this section, we propose a scheme that stimulates nodes to participate in the game, so that messages can be forwarded.

The main idea of our scheme is to influence the players' strategy by introducing a carefully designed transaction fee. Denote by $X(m, x)$ the transaction fee of the message m at price x. In the message trading game, this transaction fee is included in the final purchase price. That is to say, the seller gives out some of her profit as transaction fee when accessing the CCC to clear the transaction. The advantage of introducing the transaction fee is that, by carefully choosing a formula for $X(m, x)$, we can change the seller's best strategy in the game, such that her offer in the first round is a "reasonable" price for the message. This price is "reasonable" in the sense that it makes the transaction profitable for both parties. That is, both parties will have positive utilities in the game. Recall that a node request a message on which it has at least θ higher delivery probability. In our scheme, a message trading game takes place only on a message m such that $V_B(m) - V_S(m) - T(m) - P(m) > 2\sigma$. Furthermore, accepting this "reasonable" price is also to the best interest of the buyer.

Our designed formula for $X(m, x)$ is as follows:

$$X(m,x) = \begin{cases} \gamma & \text{if } x \leq \frac{V_S(m)+V_B(m)+T(m)-P(m)}{2} \\ k\left(x - \frac{V_S(m)+V_B(m)+T(m)-P(m)}{2}\right) + \gamma & \text{o.w.,} \end{cases}$$

where $\gamma \leq (V_B(m) - V_S(m) - T(m) - P(m))/2 - \sigma$ is a very small primary transaction fee, and $k = 2 - 2\gamma/(V_B(m) - V_S(m) - T(m) - P(m))$. We note that the advantage of using the proposed formula is twofold. On one hand, since γ is very small, the transaction fee is also very small compared with the utilities got by the players, when the purchase price is in reasonable range ($x \leq (V_S(m) + V_B(m) + T(m) - P(m))/2$). On the other hand, using the proposed formula, the equilibrium purchase price is $(V_S(m) + V_B(m) + T(m) - P(m))/2$, which

[1] We do not deduct the bargaining costs here, because they are variables depending on the design of the bargaining scheme.

[2] This is the case when, for example, nodes are equipped with GPS systems, which enable they to calculate the length of communication time by geometry, given communication ranges, speeds, and heading directions of the two nodes.

makes the utility difference between seller and buyer is only γ. When γ converges to 0, seller and buyer will have the same utility in the transaction.

Figure 1 gives a complete description of our scheme.

Suppose two nodes come into the communication range of each other.

1) The two nodes exchange the lists of the message they carry. Suppose one of the nodes (buyer B) wants to buy a message m from the other node (seller S).
2) In each round $r \leq R$, starting from $r = 1$, the seller S makes a proposal (a purchase price) x, which the buyer B then either accepts or rejects. Acceptance ends the game while rejection leads to round $r + 1$.
3) If an agreement is reached, the seller S transmits the message m to the buyer B; and the buyer B pays x to the seller S. If no proposal is ever accepted then the outcome is the disagreement event.
4) When the seller S has a connection to the credit clearance center (CCC), it clear the transaction and pays transaction fee $X(m, x)$.

Fig. 1. Message Trading Scheme.

The following theorem shows the analysis result of our scheme. Due to limitations of space, we omit the proof here. For details of proof, please refer to our technical report [14].

Theorem 2: If the above scheme is used, then there exists a unique subgame perfect equilibrium. In the subgame perfect equilibrium, the seller S always proposes

$$x^\star = \frac{V_S(m) + V_B(m) + T(m) - P(m)}{2},$$

in each round r; the buyer B only accepts proposal x for which

$$x \leq \begin{cases} \frac{V_S(m)+V_B(m)+T(m)-P(m)}{2} + \sigma & \text{if } r < R \\ V_B(m) - P(m) & \text{if } r = R, \end{cases}$$

and rejects any other proposals.

Note that the structure of message trading game allows the game to continue for R rounds, but under our scheme, an agreement is reached immediately at price $x = (V_S(m) + V_B(m) + T(m) - P(m))/2$ in the subgame perfect equilibrium.

IV. Evaluations

In this section, we integrate our scheme with MV routing [2] and evaluate it using GloMoSim [13].

A. Methodology

We consider wireless networks with 10, 20, 30, and 40 mobile nodes randomly distributed in a terrain area of 10 km by 10 km. Each node has three locations in the physical terrain, and randomly travel among these locations at a speed uniformly chosen between 10 m/s and 30 m/s. After reaching its destination, the node stays there for 5 minutes.[3] Nodes use IEEE 802.11 (at 11Mbps) as the MAC layer protocol. The radios' transmission range is set to 250 meters. Nodes broadcast hello message every 1 second. The length of time unit used in probabilistic routing protocols is set to 1 minute.

Nodes generate messages with uniform time interval of 10 minutes. The destination of the message is randomly selected from the other nodes. A message is dropped if it can not be forwarded to another node in 1 hour. Each simulation runs for 24 hours, and is repeated 10 times with different random seeds. Every node has an initial credit of 5000, and pays 100 credit for each delivered message.

Node Behaviors: In our evaluations, we compare two types of node behavior:

- Cooperative behavior: Following the scheme faithfully.
- Selfish behavior: Not be willing to participate in message forwarding for others. We report results when 30% and 70% of the nodes are selfish.

B. Impacts of Selfish Behavior on Cumulative Utility

In our first set of evaluations we demonstrate that being cooperative is better than being selfish in terms of cumulative utility.

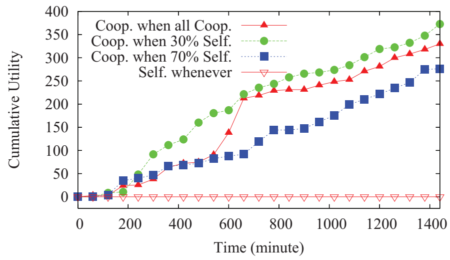

Fig. 2. Cumulative utilities obtained by node 13 in a network with 20 nodes. Four cases are compared: A) Behaving cooperatively when all the other nodes are cooperative; B) Behaving cooperatively when 30% nodes are selfish; C) Behaving cooperatively when 70% nodes are selfish; D) Behaving selfishly no matter what the others do.

Figure 2 shows the cumulative utilities of node 13 in a 20-node network . We note that the results for the other players are similar to that of player 13. We can see that the node always has positive and increasing cumulative utility when it behaves cooperatively no matter what the other nodes do. In contrast, the node's cumulative utility always stays at 0 throughout the simulation if it behaves selfishly. Therefore, for an individual node, being cooperative can always get a better utility than being selfish.

Figure 3 shows the cumulative distribution function (CDF) of the achieved cumulative utilities for 400 tracked node records. This result is composed of 10 repeated simulations with different random seeds. Each simulation is on a network with 40 nodes. The figures show the results when all nodes are cooperative and when some of them are selfish. We observe that the cumulative utilities achieved by collectively being

[3] We evaluate the performance of our schemes on a 3-waypoint mobility model instead of human movement traces, because the time spans of available human movement traces are not long enough for this evaluation. The range of movement speed roughly captures the average driving speeds in city.

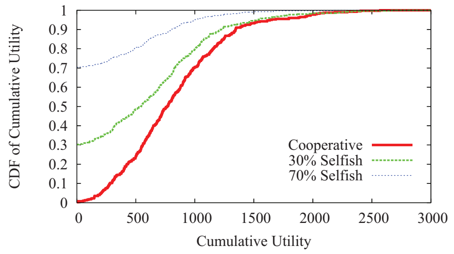

Fig. 3. CDF of cumulative utilities achieved with our schemes for 400 tracked node records. Three cases are compared: A) 100% nodes behave cooperatively; B) 30% nodes behave selfishly; C) 70% nodes behave selfishly.

cooperative are higher than those of partially being selfish. Intuitively, this is because when more nodes are cooperative, nodes get more opportunities to forward messages, which results in getting more utilities. These figures again demonstrates that being cooperative is better than being selfish in getting utility.

C. Impacts on Delivery Ratio

Our second set of evaluations are to demonstrate that our scheme improve the delivery ratio of probabilistic routing in face of selfish nodes.

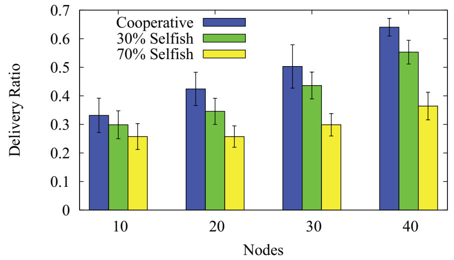

Fig. 4. Average delivery ratio as a function of the number of nodes in the network. Standard deviations are shown using lines. Three cases are compared: A) 100% nodes behave cooperatively; B) 30% nodes behave selfishly; C) 70% nodes behave selfishly.

Figure 4 shows the average delivery ratio as a function of the number of nodes in the network when all nodes behave cooperatively and when some of the nodes behave selfishly. The figures show that the average delivery ratio increases with the number of nodes in the network, and the highest delivery ratio is always achieved by 100% being cooperative, which can be guaranteed by our incentive schemes. However, the larger number of nodes is, the more significant advantage of using our schemes is. Particularly, our schemes achieves 11.1-22.8% and 28.8-75.8% gain in delivery ratio in the cases where 30% and 70% of the nodes behave selfishly, respectively.

V. Related Work

In this section we briefly review the related works on incentive-compatible message/packet forwarding in wireless networks.

We focus on the works using credit, or virtual money, as compensation for participating the game and forwarding packets. Buttyan and Hubaux was the first to use virtual money for the packet forwarding [3]. Their solution needs the help of a piece of tamper-proof hardware on each node. Zhong et al.'s Sprite [16] is another simple credit-based solution but it does not require tamper-proof hardware. Another solution to this problem was due to Jakobsson et al., using a micro-payment scheme [8]. Zhong et al. combined problems of route selection and packet forwarding and designed a protocol using an integrated approach of game theory and cryptography [15]. Lee et al. presented a secure incentive framework for commercial ad dissemination in vehicular networks [9]. Different from existing works, our scheme integrates bargaining and probabilistic routing to provide incentives for message forwarding in opportunistic networks.

VI. Conclusions

In this paper, we have presented a novel and practical scheme to integrate incentive compatibility into a class of probabilistic routing protocols for opportunistic networks. We have integrated our scheme with MV routing and evaluated them using GloMoSim. Evaluation results have shown that: A) behaving cooperatively is to the best interest of each node under our scheme; B) our incentive scheme can substantially improve network delivery ratio (11.1%-75.8% in our evaluated settings) in the presence of selfish nodes.

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