Generalized Second Price Auction in Multi-Path Routing with Selfish Nodes

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***Abstract*— We model the multi-path routing with selfish nodes as an auction and provide a novel solution from the game-theoretical perspective. By adapting the idea of generalized second price (GSP) payment originating from Internet advertising business and developing pertinent policies for multi-hop networks, we design a mechanism that results in Nash equilibria rather than the traditional strategyproofness, which alleviates the over-payment problem of the widely used Vickrey-Clark-Groves (VCG) payment mechanism. We first provide rigorous theoretical analysis of the proposed mechanism, showing the equilibrium behavior and bounds of the over-payment alleviation, and then evaluate the effectiveness of this protocol through extensive simulations.**

***Index Terms*— Mechanism design, game theory, routing.**

I. Introduction

Multi-path routing is an important routing technique in both fixed and wireless networks. This is not only because multi-path routing can provide load balancing and route resilience, it is also because multi-path routing can be used to resolve some specific issues in the networks. In Internet, for example, traffic are routed over multiple paths due to some administrative reasons. Another example can be seen in wireless ad hoc networks, in which traffic are preferred to be routed through multiple paths in order to avoid excessive interference and drainage of the device battery on a specific path.

When the nodes in a network are non-cooperative, routing becomes a very challenging problem. In this context, each node is *selfish* (often referred to as *rational* in game theory literature); she is not willing to spend her own resources to forward packets for other nodes. And yet each node relies on other nodes to forward her packets. Single-path routing in wireless ad hoc networks with non-cooperative nodes has been an active research area. Marti *et al.* proposed the so called watchdog and pathrater mechanisms to deal with selfish nodes [1]. Buchegger *et al.* proposed a protocol called CONFIDANT, with the objective to monitor the behavior of nodes, evaluate the reputation of corresponding nodes and punish selfish nodes [2]. Another approach to cope with selfish nodes is to stimulate them to cooperate. A node earns credit by providing forwarding service to other nodes and has to pay to get service from other nodes [3]. Obviously, the payment received by a service-providing node should be large enough to cover the cost incurred to provide the service so this node has enough incentive. However, selfish nodes may cheat over their cost to maximize their payoff. This necessitates some payment mechanisms that encourage a service-providing node to reveal her true cost.

For this purpose, the Vickrey-Clark-Groves (VCG) payment mechanism has been applied in single-path routing [4][5] and multi-path routing [6] scenarios. With VCG payment mechanism, a node maximizes her payoff only when she reveals her true cost. However, VCG suffers from the inevitable over-payment problem [7][8]. Efforts to alleviate this problem have been made in single-path routing scenario [9]. In this paper, we address this problem in the multi-path routing scenario. We propose a mechanism that uses generalized second price (GSP) auction which originates from Internet advertising [10][11]. Although GSP achieves lower over-payment than VCG, its existing form used in Internet advertising does not guarantee each node to reveal its true cost. Therefore, we will design a mechanism which results in Nash equilibria for all nodes to behave honestly.

The remainder of this paper is organized as follows. Section II discuss the abstracted network representation and build the mechanism framework for the auction. Following that, Section III provides rigorous theoretical analysis of the proposed mechanism, and Section IV evaluates its effectiveness through extensive simulations. Section V reviews the literature and Section VI concludes this paper.

II. System Model

A. Network Abstract

A network is formed by a finite number of nodes, which are denoted by $\mathcal{V} = \{1, 2, \ldots, n\}$. The edge $(i, j) \in \mathcal{E}$ between node i and node j represents the communication link between them. In this way, the network could be represented by a weighted graph $\mathcal{G} = \{\mathcal{V}, \mathcal{E}, \mathcal{W}\}$, where $\mathcal{W}$ is the set of weights representing the cost on each edge (i, j).

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The player set of this multi-path routing game are the intermediate nodes. We assume each intermediate node incurs a per-packet cost for forwarding traffic, and this cost is private to herself. For the sake of simplicity, we assume in this paper that there is no collusion among the nodes. In the route discovery process, each node bids with the reported cost of the outgoing links. After obtaining all the link information and constructing the network graph, the routing protocol orders the node-disjoint paths as the Least Cost Path (LCP) candidates denoted as $\{LCP_i\}$, with $i < j$ if $\mathcal{C}_i < \mathcal{C}_j$, where $\mathcal{C}_i$ is the cost of LCP_i. Assume that the first m LCP candidates are selected for packet forwarding. A fraction of data traffic f_i will be forwarded through LCP_i. The per-packet payment is calculated according to the routing decision and the bids placed by intermediate nodes.

The bid of each intermediate node is kept confidential by encryption and can only be exposed to the destination and source nodes. Once the route discovery process is finished, nodes cannot change their bids before the transmission is complete or rerouting is triggered. Therefore, we model this auction as a simultaneous-move, one-shot strategic game.

Following the definition in game theory [12], node i's per-packet payoff or utility u_i is given by

$$u_i = p_i - c_i, \tag{1}$$

where c_i is node i's cost and p_i is the payment made by the source to node i.

While it is obvious each intermediate node i's objective is to maximize her utility by giving a proper bid, the goal of the entire system is to minimize the total transmission cost by allocating proper traffic among the m paths, subject to certain constraints $\{\mathcal{P}^{(n)}\}$, which represent a set of policies we will discuss in detail later. Therefore, we have

$$\begin{aligned} \text{node } i: \quad & \max\{u_i f_i\} \\ \text{system}: \quad & \min\left\{\sum_{j=1}^{m}(\mathcal{C}_j f_j)\right\} \\ & s.t. \quad \{\mathcal{P}^{(n)}\} \end{aligned} \tag{2}$$

B. Mechanism Design

We need to design a mechanism to calculate the payment. The objective of such a mechanism is to stimulate the rational players being honest without hurting their utility.

VCG (sometimes is also called *second price auction*) payment is a widely used strategyproof mechanism for network routing [4][5][13]. In classical auction context, VCG requires each player i in the auction pays the opportunity cost that her presence introduces to all the other players [14]. For the multi-path routing game, if m LCP candidates are used, the VCG per-packet payment to node i for serving LCP_k is given by

$$\begin{aligned} p_{i,k}^{VCG} &= \frac{1}{f_k}\left[\sum_{j=k}^{m}\mathcal{C}_{j+1}f_j - \left(\sum_{j=k+1}^{m}\mathcal{C}_j f_j + [\mathcal{C}_k - c_{i,k}]f_k\right)\right] \\ &= \frac{\sum_{j=k}^{m}[\mathcal{C}_{j+1} - \mathcal{C}_j]f_j}{f_k} + c_{i,k}, \end{aligned} \tag{3}$$

where $c_{i,k}$ denotes the cost of node i serving LCP_k.

VCG is strategyproof, however, it suffers from the over-payment problem [7][8]. In order to reduce the over-payment, we propose to adopt another mechanism called generalized second price (GSP) auction. GSP is currently used by Yahoo! and Google in Internet advertising auction [10][11], where advertisers bid for multiple advertisement positions for each keyword appearing on the search engine. Instead of calculating the opportunity cost of all the other players, GSP only considers the player who obtains the next position. Therefore in the multi-path routing game, if node i is on LCP_k, then GSP per-packet payment only considers the cost of other nodes on LCP_k (excluding herself) and LCP_{k+1}, and is given by

$$p_{i,k}^{GSP} = \frac{\mathcal{C}_{k+1}f_k - [\mathcal{C}_k - c_{i,k}]f_k}{f_k} = \mathcal{C}_{k+1} - \mathcal{C}_k + c_{i,k} \tag{4}$$

Comapring (3) and (4), it is obvious that GSP achieves lower over-payment than VCG. However, the existing GSP mechanism used in Internet advertising auction has a unpleasant flaw that generally it does not have any truth-telling equilibrium [10][11], where each node truthfully reveals her private type. According to our analysis, this flaw arises from the fact that Yahoo! and Google do not have the ability to control or adjust the number of clicks by users per unit time for each advertisement position. In our mechanism design, we eliminate this flaw by adding a policy which controls the traffic allocation among the selected LCP candidates.

C. Policy Discussion

In the network abstract, the constraints represent a set of policies $\{\mathcal{P}^{(n)}\}$. Such policies are an important part of our mechanism design. The basic policies are as follows:

$\mathcal{P}^{(1)}$: *The number of selected LCP candidates m is always less than the total number of LCP candidates between the source and destination.* This policy is natural and easy to understand. Note that the case with $m = 1$ is trivial since it reduces the problem to single-path routing, where our proposed mechanism behaves exactly the same as VCG does. Therefore, we only consider $m \geq 2$ in the following discussion.

$\mathcal{P}^{(2)}$: *The fraction of data traffic forwarded through each selected LCP follows that $\sum_{i=1}^{m} f_i = 1$ and $f_1 > f_2 > \cdots > f_m > 0$.* Since all the packets needed to be forwarded to the destination, it is natural that the traffic fractions sum to unity. Moreover, we emphasize that $\forall i, f_i > 0$ since any $f_i = 0$ will reduce m. Also, the fact that the fractions of traffic allocated to the m LCP candidates appear in descending order is compatible to the entire system's goal of minimizing total cost, since LCP_i with larger i tends to introduce higher cost per packet.

$\mathcal{P}^{(3)}$: *For any $p < q$, we have $[\mathcal{C}_{p+1} - \mathcal{C}_p]f_p > [\mathcal{C}_{q+1} - \mathcal{C}_p]f_q > [\mathcal{C}_{q+1} - \mathcal{C}_q]f_q$.* We refer policy $\mathcal{P}^{(3)}$ as the *traffic allocation condition*. The first inequality $[\mathcal{C}_{p+1} - \mathcal{C}_p]f_p > [\mathcal{C}_{q+1} - \mathcal{C}_q]f_q$ says that a player on a path with less total cost tends to have a better utility than one on a path with more total cost. The second inequality $[\mathcal{C}_{p+1} - \mathcal{C}_p]f_p > [\mathcal{C}_{q+1} - \mathcal{C}_p]f_q$

says that by overbidding to go from a path with less total cost to one with more total cost, a player cannot increase her utility. Combing the two gives the condition we have stated in $\mathcal{P}^{(3)}$. As we will see later, this condition guarantees a truth-telling node's utility if some other nodes are trying to game the routing protocol.

$\mathcal{P}^{(4)}$: *Any other practical policies that do not conflict with* $\mathcal{P}^{(1)} \sim \mathcal{P}^{(3)}$ *but are essential to the network under consideration.* We introduce $\mathcal{P}^{(4)}$ to reflect those technical and/or administrative polices existing in practical networks and routing protocols. For example, in wireless networks, a certain link usually has a limit for traffic carried over unit time due to device battery life or transmission interference. It is also common to observe in the Internet routing that sometimes one AS does not want her traffic through a certain intermediate AS exceeding a threshold due to administrative reasons. A simple example of $\mathcal{P}^{(4)}$ could be the constraints that $f_i \leq \mathcal{L}_S^i, (1 \leq i \leq m)$, where $\mathcal{L}_S^i$ is the limit of source's traffic fraction sent over LCP_i. The detailed discussion of $\mathcal{P}^{(4)}$ is beyond the scope of this paper. We only present it here to provide a means of combining our incentive polices discussed in this paper with the existing network architecture and routing protocols in the literature. Once $\{\mathcal{P}^{(n)}\}$ have a feasible region, the selection of $\mathcal{P}^{(4)}$ does not affect the incentive analysis of our proposed mechanism. Alternatively, as in [6], one can take into account bandwidth constraints explicitly when formulating the traffic allocation policy.

III. Theoretical Analysis

In this section, we give theoretical analysis of the proposed mechanism. More specifically, we are interested in this mechanism's equilibrium behavior and over-payment alleviation performance.

Theorem 1: In the multi-path routing game, under the traffic allocation condition $\mathcal{P}^{(3)}$*, there are Nash equilibria for all player nodes to honestly bid their true cost.*

Proof: Let $a_k^{(r)}$ be the action of node k bidding her true cost of link k' in route discovery. Let $\overline{a}_k^{(r)} \neq a_k^{(r)}$ be a different action. Let $a_{-k}^{(r)}$ be the action profile of all the other nodes behave honestly in this stage. For the prospective utility, we will show that $u_k(\overline{a}_k^{(r)}, a_{-k}^{(r)}) \leq u_k(a_k^{(r)}, a_{-k}^{(r)})$. There are several cases.

- Case (1): With $a_k^{(r)}$, Link k' was on LCP_j, $j > m$, and node k exaggerates the cost of k'.
- Case (2): With $a_k^{(r)}$, Link k' was on LCP_j, $j > m$, and node k understates the cost of k'.
- Case (3): With $a_k^{(r)}$, Link k' was on LCP_i, $1 < i \leq m$, and node k exaggerates the cost of k'.
- Case (4): With $a_k^{(r)}$, Link k' was on LCP_i, $1 < i \leq m$, and node k understates the cost of k'.

In each case, there are several possible outcomes depending on the bids. We analyze each case as follows.

In case (1), exaggerating the cost could not increase the chance of LCP_j being selected, i.e., $u_k(\overline{a}_k^{(r)}, a_{-k}^{(r)}) = u_k(a_k^{(r)}, a_{-k}^{(r)}) = 0$.

In case (2), understating the cost could increase the chance of LCP_j being selected. Recall that $\mathcal{C}_j$ as the cost of LCP_j if node k bids the true cost. After understating the cost of link k', if LCP_j is still not selected, then node k will not make a profit and $u_k(a_k^{(r)}, a_{-k}^{(r)}) = u_k(\overline{a}_k^{(r)}, a_{-k}^{(r)}) = 0$. If LCP_j is selected after understating the cost of k', it becomes one of the selected LCP candidates $LCP_i, 1 \leq i \leq m$. Note for true cost $\mathcal{C}_j > \mathcal{C}_{i+1}$. Therefore $u_k(\overline{a}_k^{(r)}, a_{-k}^{(r)}) = [\mathcal{C}_{i+1} - \mathcal{C}_j] \cdot f_i < 0 = u_k(a_k^{(r)}, a_{-k}^{(r)})$.

In case (3), there are three possibilities. First, with $\overline{a}_k^{(r)}$, if link k' becomes not selected, then $u_k(\overline{a}_k^{(r)}, a_{-k}^{(r)}) = 0 < u_k(a_k^{(r)}, a_{-k}^{(r)})$. Second, with $\overline{a}_k^{(r)}$, if link k' is moved from LCP_i to $LCP_j, i < j \leq m$, according to policy $\mathcal{P}^{(3)}$, we have $u_k(\overline{a}_k^{(r)}, a_{-k}^{(r)}) = [\mathcal{C}_{j+1} - \mathcal{C}_i]f_j < [\mathcal{C}_{i+1} - \mathcal{C}_i]f_i = u_k(a_k^{(r)}, a_{-k}^{(r)})$. Third, with $\overline{a}_k^{(r)}$, if link k' is still on LCP_i, the nodes on LCP_{i-1} do not have incentive to switch the position down because their utilities on LCP_{i-1} are guaranteed by policy $\mathcal{P}^{(3)}$, which coincides with the locally envy-free property [11]. Hence $u_k(\overline{a}_k^{(r)}, a_{-k}^{(r)}) = u_k(a_k^{(r)}, a_{-k}^{(r)})$.

In case (4), there are two possibilities. First, with $\overline{a}_k^{(r)}$, if link k' is still on LCP_i, then $u_k(\overline{a}_k^{(r)}, a_{-k}^{(r)}) = u_k(a_k^{(r)}, a_{-k}^{(r)})$. Second, with $\overline{a}_k^{(r)}$, link k' is moved from LCP_i to LCP_j, $1 \leq j < i$. Note for true cost $\mathcal{C}_i > \mathcal{C}_{j+1}$. Therefore $u_k(\overline{a}_k^{(r)}, a_{-k}^{(r)}) = [\mathcal{C}_{j+1} - \mathcal{C}_i]f_j < 0 < u_k(a_k^{(r)}, a_{-k}^{(r)})$.

Therefore node k can only maximize her utility by bidding the true cost of link k', i.e., revealing the private type. Thus the proof is completed. ■

Theorem 1 is important in the sense that it demonstrates that by policy $\mathcal{P}^{(3)}$, our mechanism results in a set of Nash equilibria where each player node reveals the true cost. Any additional police $\mathcal{P}^{(4)}$ will lead to a certain Nash equilibrium among them. Based on Theorem 1, we now analyze the over-payment at any of these equilibria.

Theorem 2: In any of these Nash equilibria, the over-payment of GSP is always less than VCG.

Proof: It is easy to show that the amount of over-payment to each intermediate node actually equals her utility, and it is the same for all the intermediate nodes on the same path. Let n_i, $1 \leq i \leq m$, denote the number of intermediate nodes on LCP_i. Consider the ratio r_i of the over-payment introduced by GSP to VCG on LCP_i:

$$r_i = \frac{[\mathcal{C}_{i+1} - \mathcal{C}_i] \cdot f_i \cdot n_i}{\sum_{j=i}^{m} [\mathcal{C}_{j+1} - \mathcal{C}_j] \cdot f_j \cdot n_i} \quad (5)$$

Remember $\mathcal{P}^{(3)}$ guarantees that for any $p < q$, we have $[\mathcal{C}_{p+1} - \mathcal{C}_p] \cdot f_p > [\mathcal{C}_{q+1} - \mathcal{C}_q] \cdot f_q$, therefore we can derive the lower and upper bounds for this ratio as:

$$r_i^{lower} > \frac{[\mathcal{C}_{i+1} - \mathcal{C}_i] \cdot f_i}{[\mathcal{C}_{i+1} - \mathcal{C}_i] \cdot f_i \cdot (m - i + 1)} = \frac{1}{m - i + 1} \quad (6)$$

$$r_i^{upper} < \frac{[\mathcal{C}_{i+1} - \mathcal{C}_i] \cdot f_i}{[\mathcal{C}_{m+1} - \mathcal{C}_m] \cdot f_m \cdot (m - i + 1)} \quad (7)$$

Now we consider the ratio r between the total over-payment introduced by GSP to VCG, and derive its lower and upper bounds as:

$$r^{lower} > \min_i (r_i^{lower}) = r_1^{lower} = \frac{1}{m} \quad (8)$$

$$r^{upper} < \max_i (r_i^{upper}) = r_m^{upper} = 1 \quad (9)$$

Therefore, we conclude that at any of these Nash equilibria, the ratio of over-payment by GSP to VCG is bounded by $\frac{1}{m} < r < 1$. Thus the proof is completed. ■

IV. Performance Evaluation

The proposed mechanism can be easily applied to the existing routing architecture with minor modifications. For example, considering applying this mechanism to ad hoc networks with Dynamic Source Routing (DSR) protocol. The basic route discovery and route maintenance are handled by DSR as before. The only modification is that together with the hop-count metric, the encrypted bid placed by each node is also included in the route request (RREQ) message. Accordingly, the route reply (RREP) message sent from destination to source includes the network graph constructed from the information gathered in RREQ messages. Then the routing protocol determines $f_1, f_2, \ldots, f_m$ by solving the optimization problem specified by (2). Before implementing the protocol on a testbed platform, we investigate the incentive aspect of our mechanism by extensive simulations.

We have developed an event-driven simulator using C++ (Microsoft Visual Studio 2008 Ver. 9.0.21022.8 RTM) programming language. The general settings of our simulation experiments are as follows. There are 100 nodes and 250 links in the network. To generate a network topology, these 100 nodes are randomly connected by 250 links. In the resulting network, the *degree* of a node is defined as the number of links she is connected to. The costs of links are chosen from $[1, 5]$ uniformly at random. For each intermediate node, the cost involved in forwarding a packet is dominated by the cost of the corresponding outgoing links. Each source node splits traffic among all but one of the available paths according to the specified rules. Without loss of generality, the packet generation rate at each source is assumed to be 1 packet per second, and the transmission time of a packet between two nodes is always 1 second.

First, we investigate the credit balances among different nodes, which reveals the effect of network topology. The credit balance of each node refers to the payment received by her from other nodes minus the payment made by her to others. We generate the network topology as described above. Each

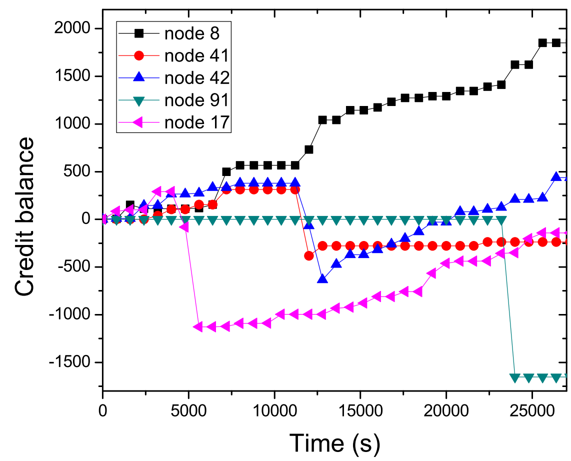

Fig. 1: Credit balances of the selected nodes.

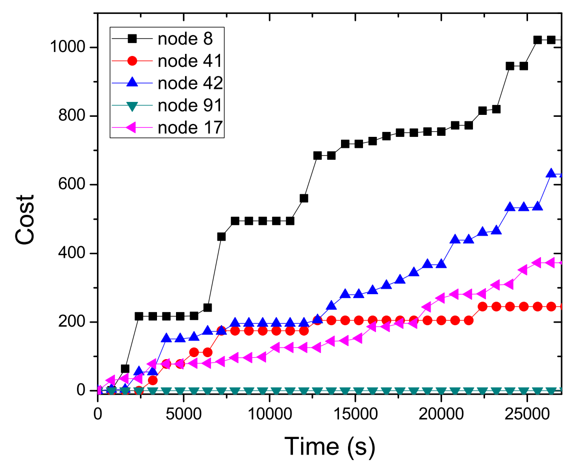

Fig. 2: Cost expenditure of the selected nodes.

node is chosen once to start a session to a random destination node. In each session, the source node generates a total of 100 packets. Once a session finishes transmission, the next session begins its transmission. This means that the credit balance of each node changes during the whole simulation period. The initial credit of each node is 0 and all nodes honestly follow the protocol. We have chosen a set of representative nodes: node 8 is a node with a high degree and low-cost links; node 41 is a node with a high degree and high-cost links; node 42 is a node with a high degree and a mix of high-cost and low-cost links; node 91 is a node with a low degree and high-cost links; node 17 is a node with a low degree and low-cost links. Fig. 1 shows the credit balances of this set of nodes. Since node 8 has a high degree and low-cost links, she is likely to be on a path to be selected. As a result, she often forwards packets for other nodes and has the most positive credit balance. On the

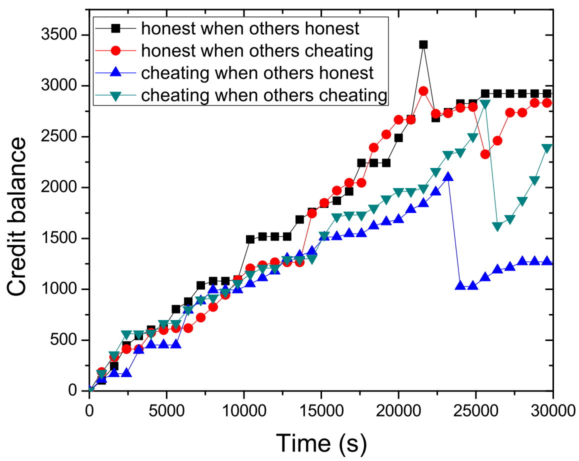

Fig. 3: Credit balance of node 85 with different strategies.

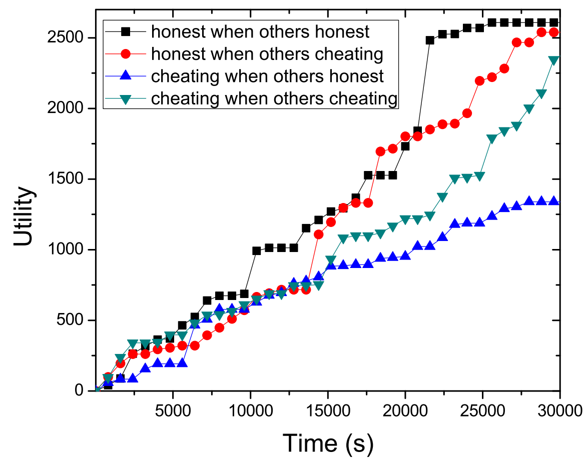

Fig. 4: Utility of node 85 with different strategies.

other hand, node 91 is sparsely connected with high-cost links, she is not likely to be chosen by source nodes. Therefore, she only pays credits to other nodes and ends up with the most negative credit balance. For the remaining nodes, nodes with more low-cost links generally have higher credit balance because they are more likely to be chosen by source nodes. Similarly, we plot the expenditures of the above set of nodes in Fig. 2. Comparing with Fig. 1, it can be seen that nodes with higher credit balance also have higher expenditure. This shows that our mechanism is fair.

Next, we investigate the effects of different strategies. There are two actions a node could choose to take during the auction, namely *honest* and *cheating*. By honest, it means that a node follows the protocol and bids with her true cost, while cheating means a node either understates or exaggerates her cost. Therefore there are totally four combinations of different strategies depending on actions by a node herself and others. While we have proved in Theorem 1 that, when others behave honestly, the strategy of being honest always leads to a better utility than the strategy of cheating, we are also interested in comparing them with the other two strategies experimentally. Therefore, we generate the cheating scenario as follows. When we decide a node to be cheating, with equal probability the reported cost is either increased or decreased based on the true cost, within a percentage of $[4\%, 20\%]$ uniformly at random. Using the same topology described above, we arbitrarily pick a node, say node 85, as the object under consideration. Results shown in Fig. 3 and Fig. 4 confirm that the strategy "honest when others honest" always outperforms "cheating when others honest". Although the proved property in Nash equilibria does not say too much about the other two strategies, we observe that for most of the time, the strategy "honest when others honest" produces the best results.

Last, we evaluate the over-payment alleviation. We randomly generate 200 topologies using the same approach and

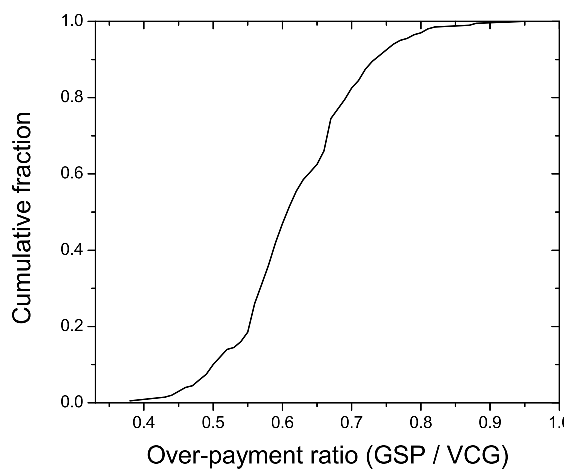

Fig. 5: CDF of over-payment ratio.

each node honestly follows the protocol. Fixing $m = 4$, we collect the over-payment of the whole network introduced by the proposed mechanism and VCG mechanism, and compute the ratio. According to the cumulative distribution function shown in Fig. 5, it is observed that the proposed mechanism always has less over-payment, and the median improvement is about 40% in this setting.

V. Related Work

Algorithmic mechanism design has been evolved into distributed computing area as distributed algorithmic mechanism design (DAMD) [15]. In particular, Feigenbaum *et al.* [4] have considered a BGP-based mechanism design for lowest-cost unicast routing in Internet. Feldman *et al.* [16] have shown how the hidden-action problem in distributed multi-hop networks can be overcome through appropriate design of contracts, in both the direct (the endpoints contract with each individual router) and recursive (each router contracts with the next downstream router) cases. Combining economics concepts and cryptographic techniques with distributed algorithmic mechanism design seems to be a promising direction in the ad hoc networks research.

Buttyan and Hubaux proposed nuglets [17] to serve as incentives to cooperate. Nuglets is the per-hop payment carried in every packet. The authors also proposed another form of incentives as counters [3]. Each source node pays for the cost and each intermediate node who forwards the packet gets her payment accordingly. The limitation of such schemes is that both nuglets and counters rely on a secure hardware in each node. Anderegg and Eidenbenz proposed Ad hoc-VCG [5] to calculate the payment. VCG has been previously used in wired networks [4], which is a strategyproof and ex-post efficient scheme. However, it suffers from the over-payment [7][8] problem. A simple credit-based system is proposed in [18], which does not require a tamper-proof hardware in each node for credit maintenance. Combining VCG with a cryptographic technique [13], Zhong *et al.* proposed a incentive-compatible solution which corresponds to a relaxation of a dominant-action solution. VCG mechanism have also been used for multi-path routing in [6] and [19]. Wang *et al.* proposed OURS [9] to consider the situation that both the relay nodes and the service requestor (either the source or the destination or both) are selfish. They studied the unicast routing system with the concept of Nash equilibria rather than VCG strategyproof mechanism. Correspondingly, in order to alleviate the over-payment problem in multi-path routing scenario, we presented our initial result in [20].

VI. Conclusion

We have proposed a novel game-theoretical solution to the multi-path routing problem in selfish networks. By incorporating different policies, the proposed mechanism is highly compatible to existing routing protocols, which results in Nash equilibria where each player honestly reveals her true cost. By using Nash equilibrium solution as opposed to the traditional strategyproof solution, this mechanism effectively alleviates the over-payment of the well-known VCG mechanism. The effectiveness of this mechanism has been shown through theoretical analysis and extensive simulations.

There are several interesting research problems we are interested to solve in the future. First, although we have rigorously analyzed the incentive aspect (namely, $\mathcal{P}^{(1)} \sim \mathcal{P}^{(3)}$) of the proposed mechanism, we still want to better understand how incentive parts interact with other technical and/or administrative parts (namely, $\mathcal{P}^{(4)}$). Second, since it is not necessary that a selfish node who behaves honestly during the routing stage would always behave honestly during the forwarding stage, it leaves a problem of how to design a proper mechanism for the latter part. We are currently investigating this problem and trying to model it as a two-stage game. Third, in distributed computing area, besides rational nodes, there is another kind of *Byzantine* nodes that tend to affect the communication protocols more severely. Byzantine nodes arbitrarily deviate from the protocol due to faulty or malicious intention, and they do not care about their welfare. Dealing with both rational and Byzantine behaviors would be quite challenging yet interesting. Last, due to the many limitations of simulation, it is always more interesting to evaluate the protocol on a testbed platform to observe the effect of some practical factors.

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